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RELIABILITY TEST REPORT

MODULAR CRYOGENICS GENERATOR

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Reliability Testing of the LOX-30 Liquid Oxygen Plant was evaluated in accordance with MIL-STD-781. Reliability Tests were divided into Environmental Requirements, Reliability Growth and Reliability Demonstration Tests. Accept/reject criteria for the demonstration test was a specified MTBF of 1900 hours at the 30% risk level which was met. Four non-relevant failures occurred but had minor effect on the LOX-30 system. A failure

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distribution was established for the electro-pneumatic solenoid valves to be Log-normal.

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I. RELIABILITY ANALYSIS

A. INTRODUCTION.

1. This report is a compilation of reliability test results of the Reliability Demonstration Test for the Liquid Oxygen Modular Cryogenic Generator. The purpose of this test was to measure the reliability mean time between failure and verify that the Liquid Oxygen Generator (LOX-30) is able to perform its intended mission without excessive failures.

2. The test was conducted in accordance with the provisions of MIL-STD-781 and the procedures of the detailed test plan. Accept/reject criteria were based on Test Plan VIII with specified mean time between failure (MTBF) of 1900 hours. Total test time was 1617 hours.

3. Reliability and maintainability demonstration tests were coordinated and performed by the same personnel using similar criteria and procedures, therefore resulting data are consistent and applicable to either test.

4. The following documents were used to establish test procedures, standardize operating and maintenance requirements, and evaluate test results.

   a. MIL-STD-781B Reliability Tests: Exponential Distribution
   b. Reliability and Maintainability Demonstration Plan
   c. MIL-STD-721 Definitions of Effectiveness Terms of Reliability, Maintainability, Human Factors and Safety
   d. Reliability Engineering Handbooks, NAVAIR 00-65-502
   e. MIL-D-27210 Oxygen, Aviators Breathing, Liquid and Gas

B. BACKGROUND.

1. The Liquid Oxygen Generator is required at Naval Air Stations overseas to produce oxygen used in servicing air crew survival equipment, and medical units. The oxygen is produced as a cryogenic liquid for convenience of storage and when required the liquid oxygen is utilized to fill aircraft liquid oxygen converters and vaporized into a gas and transferred to gas cylinders.

2. The mission of the LOX-30 generator is to provide 600 to 1600 gallons per month of high purity liquid oxygen to fulfill daily operational requirements and maintain a sufficient level of oxygen storage to continue fulfilling operational requirements in the event of equipment maintenance due to failure.

C. DESCRIPTION OF EQUIPMENT.

1. The Liquid Oxygen Generator, LOX-30, consists of the following subsystems and is represented in a block diagram in Figure 1.

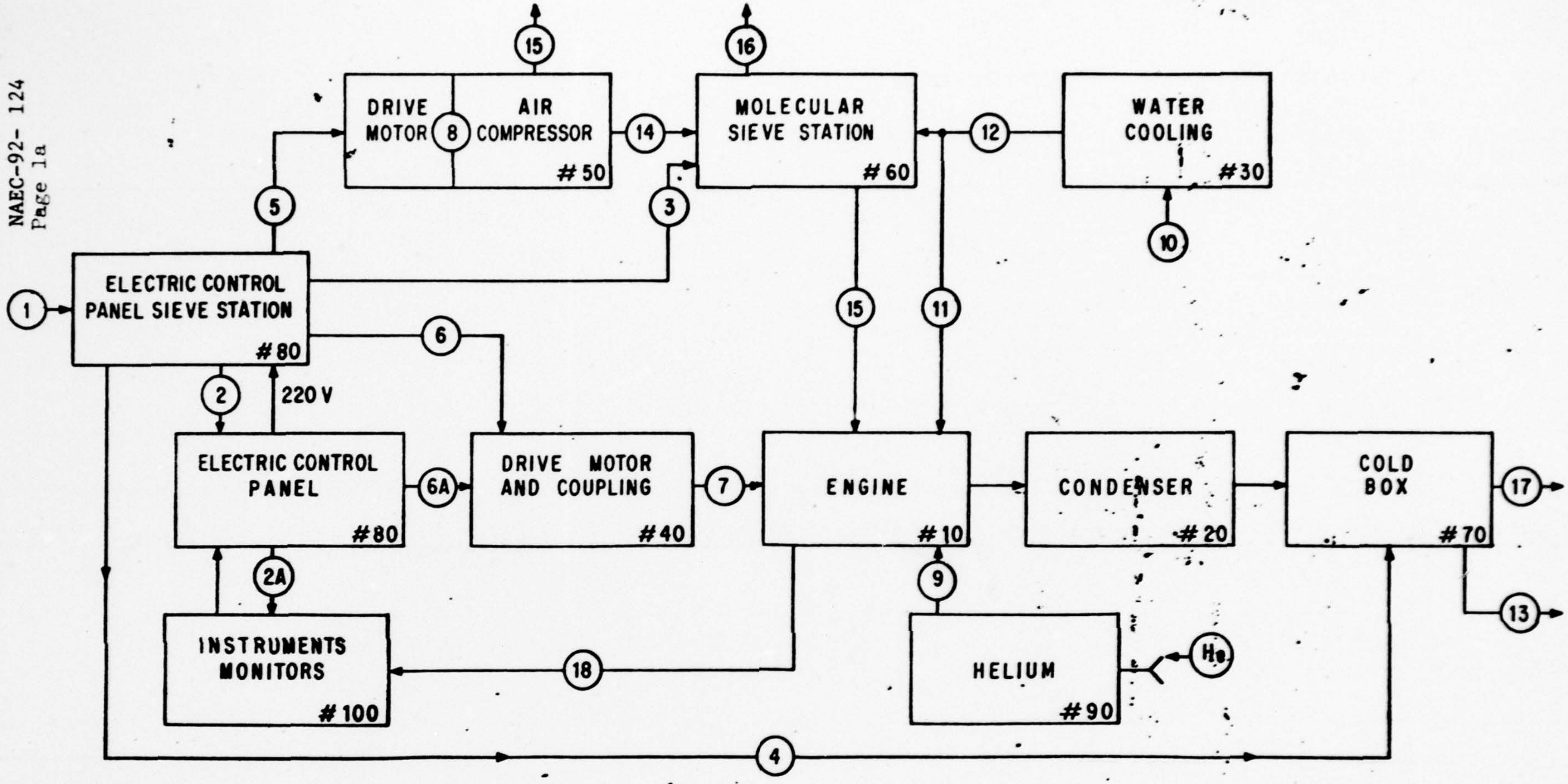


FIGURE 1

FUNCTIONAL BLOCK DIAGRAM

CODE	FUNCTION	DESCRIPTION
1.	Line Power	380/460V, 3Ø 103KW, 50/60 Hz
2.	Control Power Cryo Panel	220V, 60 Hz
	A. Instrument Panel	115/220V
3.	Control Power Sieve Station	220V, 1Ø 60 Hz 380/460 3Ø 50/60 Hz
4.	Heater Power Column E1	220V 1Ø 50/60 Hz
5.	Drive Motor Power, Compressor	380/460V 50/60 Hz 3Ø, 30KW
6.	Drive Motor Power, Cryogenerator	460V, 60 Hz 3Ø 51KW
	A. Cryogenerator Safety Cutouts	220V
7.	Torque, Engine	Function of 3Ø Power Direct Drive Thomas Type Coupling
8.	Torque, Air Compressor	Function of 3Ø Power Belt and Shive
9.	Helium Charge Line	Static Charge 230-240 psig
10.	Water Supply	20.0 gal/min
11.	Engine Water Supply	16 gal/min, 30 psig 59°F

CODE	FUNCTION	DESCRIPTION
12.	Sieve Station Water Supply	4.0 gal/min
13.	Liquid O_2 output	6.93 gal/hr, 14.7 psig
14.	Compressor Discharge Air	60 psig, 252°F;
15.	Compressor Safety Devices	
	A. Over Pressure	100 psig
16.	Molecular Sieve Station	
	A. Over Pressure Valve 901	2 bar
17.	Column	
	A. Storage Tank	3. bar
18.	Engine Sensor	
	A. Water Flow (gal/hr)	
	B. Cyl/Crankcase Temp	150°F
	C. Differential Pressure	15 psig
	D. Oil Pressure	25 to 70 psig
	E. Working Pressure	199-370 psig

2. Subsystem Number 10 - Engine. The cryogenerator engine is a self lubricated four cylinder closed cycle expansion engine cooler. An integrated working piston and displacer assembly operating in a single cylinder and connected to a common crankshaft journal form the nucleus of the engine operation and achieve the alternate compression, displacement and expansion of the working gas. The crankshaft is supported by five main and insert bearings. Axial forces are transferred to the crankcase via a thrust bearing. Lubrication is provided by an integral gear type oil pump driven by the engine via a nylon coupling.

3. Subsystem Number 20 - Header. Located atop and around the cylinder housing assemblies, the condenser consists of four condensing heads which form the top of the engine cylinders. Regenerators are positioned within each level and perform their heat transfer function as the working gas flows through each while passing between the expansion and compression chambers. The condenser heads are connected in parallel and are slotted to provide a greater cooling surface area. In the event of a cracked head, a safety valve will relieve condenser insulating space pressure at about 2 psig. An underpressure safety switch monitors condenser head pressure and will shut down the engine should excessive under pressure occur.

4. Subsystem Number 30 - Water Cooling. Continuous operation of the LOX-30 requires approximately 1200 gallons per hour cooling water at 30 to 60 psig and temperature at 59 to 70°F. Water is delivered to a manifold from where it is distributed to four helium coolers atop the cylinder housing assemblies. Each helium cooler receives water flow to remove the working gas heat of compression. Should water temperature exceed 115 ± 5°F, a thermostat in the outlet manifold is set to shut down the engine.

5. Subsystem Number 40 - Drive Motor and Coupler. The 60 HP continuous duty drive motor is horizontally mounted to the cryogenerator bed plate and is connected to the engine through a flexible coupling. The flexible coupling compensates for slight misalignment of the drive motor armature and engine crankshaft. The 60 HP, 3 phase motor is of drip-proof construction having grease packed ball bearings supporting a squirrel cage armature in the motor frame.

6. Subsystem Number 50 - Air Compressor. The Atlas Copco Air Compressor, BT-4, is a two-cylinder, two stage air cooled reciprocating compressor. The BT-4 compressor is built for working pressure up to 125 psig with one low pressure and one high pressure cylinder "V" mounted on the crankcase and equipped with an element type inlet filter. The unit contains an intermediate air cooler, a pressurized lubricating oil system with an oil pressure gage, an air-intake suction filter with silencer, compressor-air shock absorber, safety valves and pressure gauges for intermediate and discharge pressures. The air compressor is driven by a 40 HP electric, 3 phase continuous duty drive iwth a squirrel cage armature in the motor frame.

7. Subsystem Number 60 - Molecular Sieve Station. The molecular sieve station consists of an air/water aftercooler, a water separator, an oil adsorber, two molecular sieve adsorbers, and an electric heater, all mounted on a common base, and interconnected by the required piping. A power module,

which contains the electrical equipment necessary to distribute power to the other units as well as the electrical controls necessary for regeneration of the adsorbers, is mounted at the rear of the molecular-sieve-station skid.

8. Subsystem Number 70 - Cold Box (separation unit). The cold box consists of a cylindrically shaped steel shell with an externally mounted instrument and control valve panel. The shell is comprised of the following contents. A heat exchanger which cools the process air and warms the tail gas leaving the unit. Rectification column that separates the process air into pure liquid oxygen and impure nitrogen gas. Condenser/evaporator that prepares the media used in the rectification column for mass transfer. An electric heater to increase product transfer to the storage tank is provided and located on the face of the cold box.

9. Subsystem Number 80 - Electrical Control Panel. The control panel contains indicating instruments, indicating/alarm lights, lighted and unlighted push button switches, and an elapsed time meter, all of which are used in the manual and automatic control of the plant. The indicating instruments on the panel are pneumatic (for helium pressures), hydraulic (for oil pressures), and electric (ammeter and elapsed time), each of which is marked to identify the particular variable measured and displayed. Indicating lamps are used to indicate operating or non-operating circuits as well as fault or alarm indications at selected points in the system. Each indicator is marked to identify the condition or point involved. The lower section of the control panel contains a subpanel with control relays. The relay subpanel can be reached through a door on the rear of the panel.

10. Subsystem Number 90 - Helium Distribution. Helium gas is used as the working gas agent within the engine. The helium is provided in replaceable externally mounted pressurized containers. A pressure regulator and safety valve mounted on the cylinder ensures the gas is of correct pressure for introduction into the engine. The engine is pressurized to approximately 199 psig min. static pressure. During engine operation, the pressure will rise to 370 psig max. A helium filter and oil separation unit cleanses the gas before it enters the cylinder housing assembly eccentric chamber prior to introduction into the compression chamber.

11. Subsystem Number 100 - Instrumentation and Monitors. The subsystem consists of various pressure gages, pressure switches, temperature monitors, and water flow sensors, each capable of interrupting system operation should the tolerances be exceeded.

D. METHOD.

1. The reliability demonstration test was comprised of three parts, (1) Environmental Qualification, (2) Reliability Growth and (3) Reliability Demonstration, all of which were run concurrently from March 1977 through August 1977 on one sample LOX-30 system at the Lakehurst Naval Air Station Lakehurst, New Jersey. The LOX-30 system was operated with the assistance of an instruction manual provided by the contractor and in accordance with operational procedures prepared by the Naval Air Engineering Center, Code 92714.

2. Prior to initiation of the reliability and maintainability demonstration tests, the LOX-30 system had been operated by the contractor and Code 92714 a total of 710.3 hours (i.e., cryogenerator time). The balance of operational time, 1616.3 hours, was run in accordance with the reliability demonstration test plan. A brief outline of the reliability demonstration test period is enclosed in Appendix A.

II. ENVIRONMENTAL QUALIFICATIONS TEST

A. AR-113 requires that environments, both natural and induced, imposed during test shall be based on field environments.

1. The LOX-30 Liquid Oxygen Generator will be deployed as a fixed installation, properly housed within a temporary or permanent structure. Consequently, the generator will not be exposed to any adverse ambient environmental condition. Ambient air temperatures and humidity, however, do effect the net productivity of the generator, which is true for all cryogenic generators that are basically air liquefaction plants. The combination of high air temperature and high relative humidities do reduce the production rate of the LOX-30 system. The environmental test portion of the program consisted of operating the system in temperature ranges of 50° to 100°F for 1617 hours after which no relevant failures were observed. This demonstrated a system MTBF of at least 1900 hours at 70% confidence, however, the MTBF for those piece parts which experienced no failure could not be determined with any degree of confidence. Therefore further life testing to obtain additional data should be proposed followed by stress-strength testing on selected components.

2. An investigation of the environmental conditions was made to determine the maximum and minimum air temperatures and relative humidities that might be anticipated at all the overseas Naval Air Stations. These data are available in the publication, "U.S. Navy and Marine Corps Meteorological Station Climatic Summaries". It was determined that the normal weather conditions which prevail at NAEC, Lakehurst would provide sufficient temperature and humidity excursions during the environmental period of the Reliability Test Program that no special test chamber would be necessary. Because the LOX-30 is to be installed indoors, no other environmental tests (i.e., rain, sand, vibration, etc.) were to be conducted. Since the moisture content of the inlet air to the generator is the major factor upon reliability, the tests were conducted accordingly. This is true because the effect of humidity and temperature is great on production.

3. The ambient air temperatures and relative humidities were recorded by a Hygrothermograph, Model Serdex B, Bacharach Instrument Company, at the compressor air inlet.

4. Conclusion.

The test data indicates that although the LOX-30 plant did experience operating periods where atmospheric moisture content was high, no adverse operating situations were experienced during the test period.

The highest average moisture content level recorded at the overseas installations is .0215 pounds water per pound dry air. The highest level recorded during the test program at Lakehurst was .0270.

The mission requirement has been determined to be less than 4 days. Therefore the LOX-30 can adequately meet the mission. Test data are provided in Appendix B.

III. RELIABILITY GROWTH

A. This part constituted the growth test commencing after 710 operating hours on the LOX-30 system. Periodic and 1500 hour maintenance was completed by NAEC.

B. The values predicted on the Mission Analysis and the Program Master Plan are established as follows:

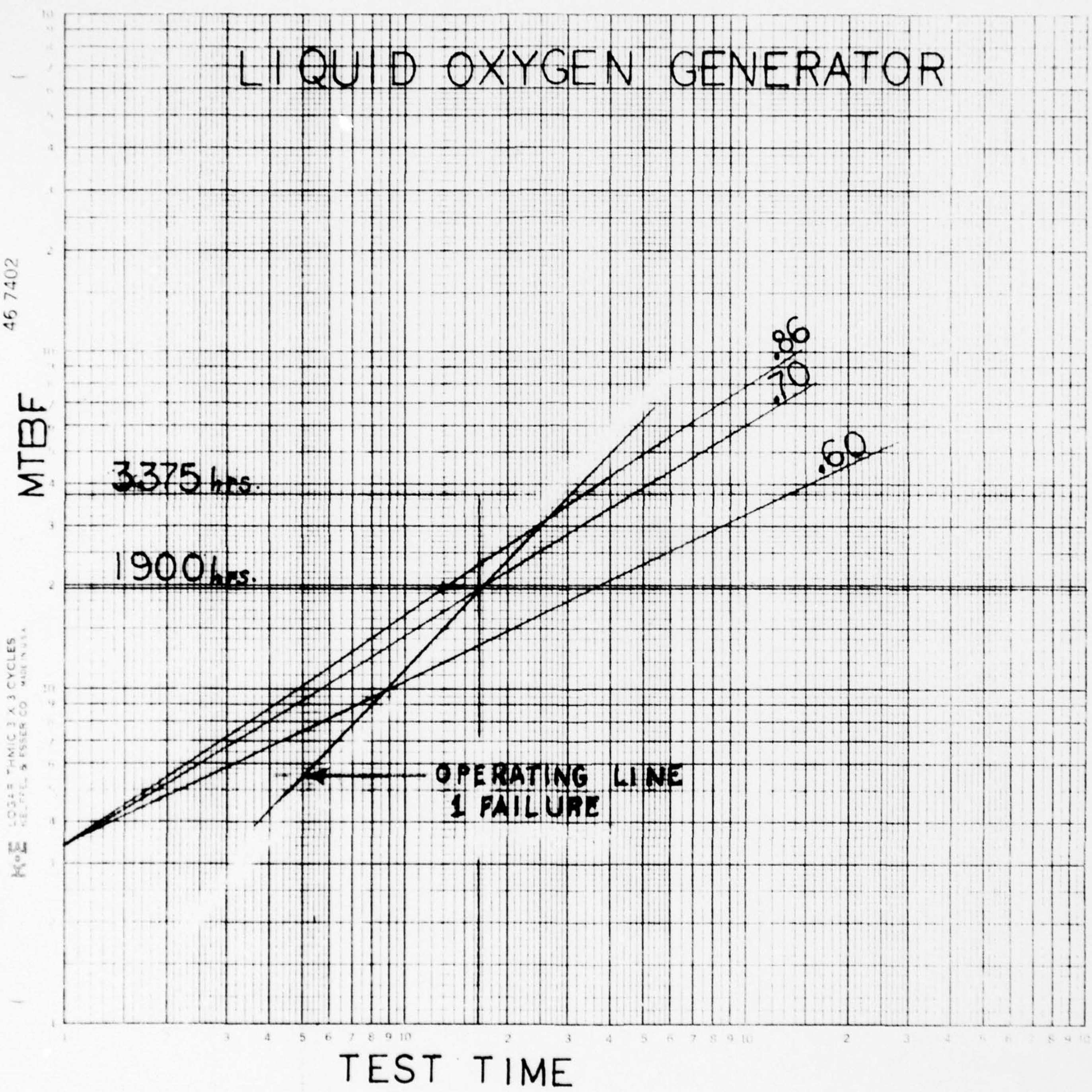
Specified MTBF		θ_o = 1900 hours
Predicted MTBF	1.77	θ_o = 3375 hours
Growth Rate		= .70

These values establish the Reliability Growth Model which is graphically presented in Figure 2. The objective of the growth program is to set a goal which will guide the development program step by step so that the reliability requirement will be met at least within the final stage development.

C. The LOX-30 System Growth Test began and continued without experiencing a relevant failure. Premature shutdowns due to power failure and water chiller breakdown did occur during the test period. At no time during the Reliability Growth Test was any major corrective maintenance taken on the LOX-30 system.

D. At 875 hours of reliability growth test time, no relevant failures had occurred. Assuming one failure in order to calculate MTBF, the growth rate at 875 hours is equal to the minimum growth rate of .60. It was concluded to continue the test to 1500 hours which would produce a growth above minimum and within the specified rate envelope at the time of the

FIG. 2


LIQUID OXYGEN GENERATOR
MTBF
3375 hrs.
1900 hrs.
.86
.70
.60
OPERATING LINE
1 FAILURE
TEST TIME
46 7402
LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.

1500 hour preventive maintenance. At this time the growth test was concluded and the test accredited toward reliability demonstration.

IV. RELIABILITY DEMONSTRATION

A. The reliability demonstration was conducted in accordance with provisions of MIL-STD-781 and the procedures of the reliability and maintainability demonstration test plan.

B. During the entire test, a total of eight personnel were used to monitor the LOX-30 system 24 hours per day, four shifts per day. When the LOX-30 was in production the following performance parameters and limits were used as a baseline for the reliability test.

I. Purity - 99.5% pure measured with a Beckmon Analyzer - Thermal Conductivity Principle.

CO_2	5.0 ppm or less
CH_4	25.0 ppm or less
N_2O	1.0 ppm or less

II. Odor - Any detection of odors shall be cause for rejection.

III. Production Rate - Minimum 6.62 gal/hr.

A graphical illustration of LOX-30 monthly and daily flow rates are presented in Appendix D.

C. PURITY.

Throughout the reliability test, purity was monitored and recorded on a daily run sheet. Numerous occasions arose where liquid oxygen purity would wander below 99.5% primarily due to excess operator adjustment and atmospheric conditions. On the average, after low purity was discovered and adjustments made, liquid oxygen purity would return to minimum 99.5% within 45 to 60 min. Constituent tests were conducted as per MIL-D-27210 on a weekly basis and where practicable. Throughout the test period Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O) were detectable, all other constituents showed no trace.

A summary of constituent test results are in Table 1.

TABLE 1

Date	Levels		Remarks
March 30	CH_4	17.5 ppm	
	N_2O	.54 ppm	
	CO_2	1.0 ppm	
April 6	CH_4	18.0 ppm	
	N_2O	.40 ppm	
	CO_2	.60 ppm	

Date	Levels		Remarks
April 13	CH_4 15.5	ppm	
	N_2O .49	ppm	
	CO_2 .79	ppm	
April 26	CH_4 14	ppm	Excess CO_2 count due to excess time on adsorber bed.
	N_2O .28	ppm	
	CO_2 13.0	ppm	
May 4	CH_4 16.5	ppm	
	N_2O .52	ppm	
	CO_2 2.0	ppm	
June 23	CH_4 19.0	ppm	
	N_2O .84	ppm	
	CO_2 2.4	ppm	
June 29	CH_4 19	ppm	
	N_2O .9	ppm	
	CO_2 2.0	ppm	
July 5	CH_4 17.5	ppm	Machine liquid level operating range unstable when samples were taken.
	N_2O .94	ppm	
	CO_2 12.0	ppm	
July 18	CH_4 13.0	ppm	Sample spoiled during transit. CO_2 count high.
	N_2O .76	ppm	
	CO_2 9.0	ppm	
July 31	CH_4 13.0	ppm	Sample taken from 500 gal storage tank and machine.
	N_2O .76	ppm	
	CO_2 3.3	ppm	
August 3	CH_4 13.5	ppm	CO_2 high due to change of adsorber bed interval 60 to 90 min per contractor manual.
	N_2O .6	ppm	
	CO_2 11	ppm	
August 11	CH_4 21.5	ppm	CO_2 high due to adsorber bed interval change.
	N_2O .6	ppm	
	CO_2 11.0	ppm	
August 17	CH_4 29.5	ppm	All levels high due to adsorber bed interval time change.
	N_2O 4.0	ppm	
	CO_2 21.0	ppm	
August 19	CH_4 26.0	ppm	90 minute time duration too long. Recommend 1 hour.
	N_2O 1.4	ppm	
	CO_2 12.0	ppm	

D. PRODUCTION RATE.

Calculations of liquid oxygen flow rate were initially conducted by attaching the product hose to a 50 gallon tank and recording the time to fill. At the time of the third week, a Rotometer from Fisher and Potter, Warminster, PA. was obtained and used as the primary instrument for obtaining liquid oxygen flow rates. Average flow rates are presented in Table II.

TABLE II

Week of	Rate	Remarks
April 4 & 11	3.17 gal/hr 3.61 gal/hr	Poor instrumentation
April 25	7.2 gal/hr	Rotometer used
June 27	7.18 gal/hr	
July 5	6.60 gal/hr	
July 18	8.12 gal/hr	500 gallon fill in 96 hrs.
August 1	7.71 gal/hr	500 gallon fill in 97 hrs.
August 8	6.93 gal/hr	
August 15	6.87 gal/hr	

Both 500 gallon tank fills will be assumed to be a representative example of field production rates of the LOX-30 system. Hourly graphs of the 500 gallon fills are presented in Fig. 3A and Fig. 3B along with a trend line of production rates. It was assumed, by examination, that the liquid oxygen production rates can follow a linear trend therefore the linear regression line was calculated. Using the method of list squares and the normal equations, the trend lines were calculated to be:

1. July 20 thru July 24
   $Y = 7.59 + .0108X$

2. August 1 to August 5
   $Y = 6.79 + .018X$

Both curves do show a positive upward slope indicating, as product time continued, a gradual increase of production rates was experienced. The calculated statistics for the two 90 hour periods are:

1. July 20 thru July 24
   (mean $\overline{X} = 8.11$ gal/hr)
   (variance $S^2 = .42$ gal/hr).

FIG 3A

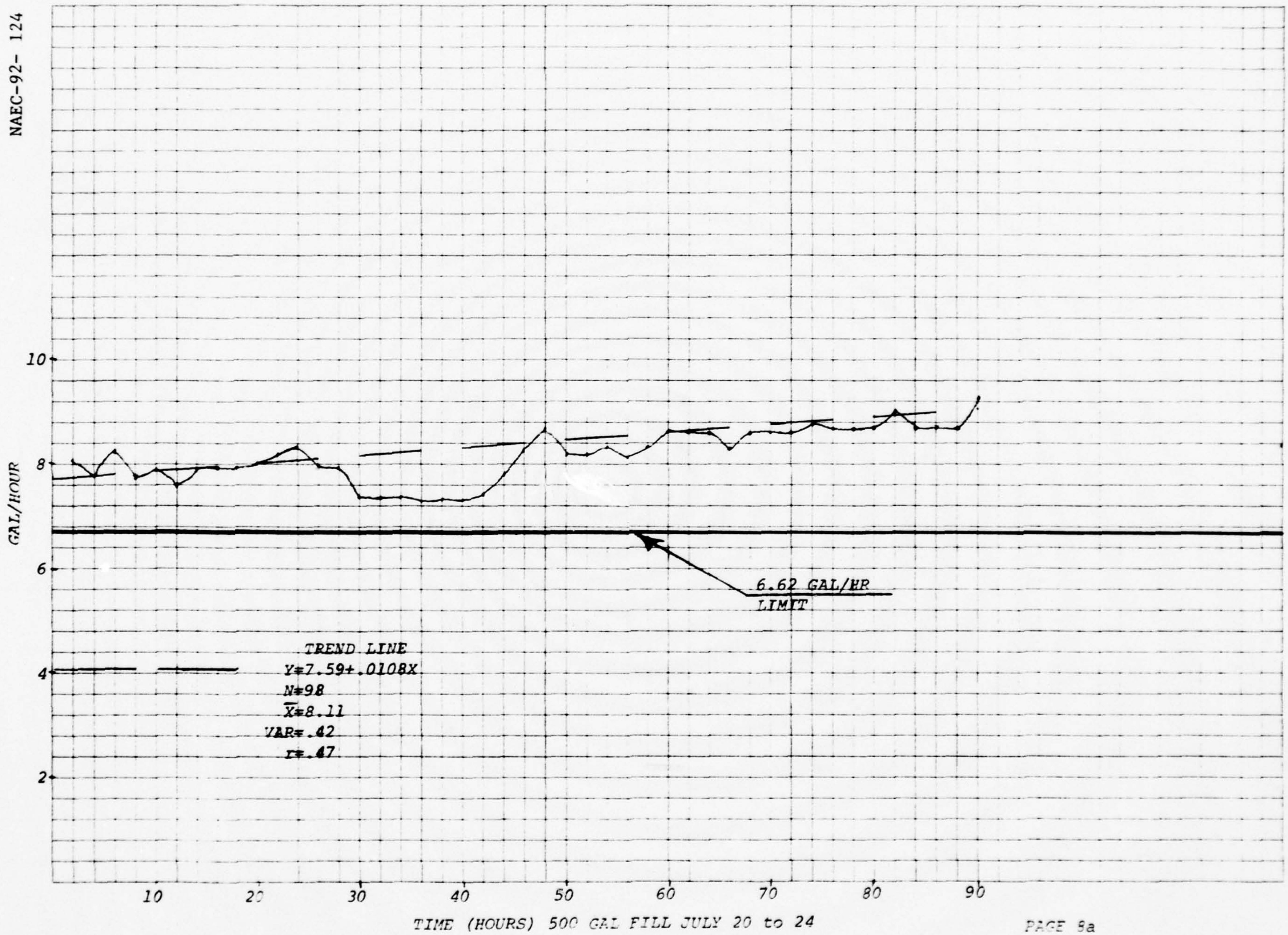

GAL/HOUR
10
8
6
4
2
10
20
30
40
50
60
70
80
90
TIME (HOURS) 500 GAL FILL JULY 20 to 24
6.62 GAL/HR
LIMIT
TREND LINE
Y=7.59+.0108X
N=98
X̄=8.11
VAR=.42
r=.47

FIG 3B

GAL/HR
10
8
6
4
2
10
20
30
40
50
60
70
80
90
6.62 GAL/HR
LIMIT
TREND LINE
Y=6.79+.018X
N=99
X̄=7.72
VAR=.91
r=.56
TIME (HOURS) 500 GAL FILL AUG 1 to 5

2. August_1 thru August 5
   (mean X = 7.72 gal/hr
   (variance) S^2 = .91 gal/hr

NOTE: The trend lines for the above periods are not to be considered the production operating curves for the LOX-30 system. Although the test data could be assumed to follow a linear trend, especially July data, the correlation coefficient for both lines are relatively low.

CORR (July)= .47
CORR (Aug) = .56

Engineering intuition dictates that production rates probably will follow a sinusoidal rather than a linear trend due to the cyclic daily variations of temperature and humidity.

E. Prior to each working week and change of shift, a pre-operational inspection and briefing was conducted for the purpose of proper system operation and parameter trends. Parameters that were of importance were recorded on daily run sheets and any peculiar trends were recorded in a daily log book. The normal test week began at 8 am Monday morning and ran through to Saturday afternoon. Deviations from the weekly test plan occurred twice. Once to simulate a 14 day continuous operating run and training purposes for Pax River personnel.

F. CLASSIFICATION OF FAILURE.

1. A failure of the LOX-30 system is defined as a malfunction which precluded performance of any required function within the limits established. Failures are classified in accordance with paragraph 5.5 of MIL-STD-781 and as follows:

a. Failure Types

Type 1 - Must stop operations to fix or repair. The equipment is unable to go through one more operating cycle or a condition exists where the safety of the equipment, or operating crew would be in jeopardy if operations were to continue. Failures in this category result in abort of the remaining mission.

Type 11 - Operations may continue, but monitoring of the failed or malfunctioning equipment is required.

Type 111 - Failure or malfunction is not serious in terms of continued operations, and repair or replacement can be safely conducted to resume operation.

Type 1V - Equipment has experienced a catastrophic or major failure.

G. FAILURE CATEGORIES.

Relevant - inability of the generator to perform one of its intended and specified functions within the specified limits.

Non-relevant - failures due to the following causes:

1. A secondary or dependent failure that is caused by the failure associated items. For every secondary failure classified as not relevant, a primary or independent failure shall be identified.

2. A test operator or test facility induced failure may be classified as non-relevant if it can be substantiated that the equipment was subject to operation or stress conditions beyond specified limits.

3. Changes to the generator to correct a deficiency that caused a failure shall not classify such a failure as not relevant until the changes have been demonstrated as a fully effective correction.

4. Preventative maintenance, servicing and adjustments are non-relevant if such actions are specified as normal maintenance in the existing or planned technical manuals.

5. Type II and Type III failures are considered non-relevant except in the event that they degenerate into Type I or Type IV failure.

H. DISCUSSION.

1. The LOX-30 generator accumulated a total of 2327 hours of which 1617 hours involved reliability testing. Operating hours were recorded by an elapsed time meter installed on the control panel and energized only when the cryogenerator was turned on. The additional compressor time is due to plant pre/post preparation. Therefore the total operating times are as follows:

Total Compressor Operating Time	1732 hours
Total LOX Production Time	1617 hours

A total of four failures were recorded during the test. Each failure is documented by the Failure Reports which are included in Appendix C.

2. The failures and their classifications are as follows:

Failure No.	Description	Type
1	Quick Disconnect Fitting	II
2	Electro-Pneumatic Solenoid Valve	III
3	Solenoid Air Valve	III
4	Pipe, Compressor Discharge	III

Of the above failures none were of the relevant category.

3. Accept/reject criteria for the demonstration were in accordance with test plan VIII of MIL-STD-781. The test is a sequential type with a discrimination ratio of 2.0:1 with an alpha and beta risk of 30%. Requirements of this test plan are presented in Figure 3. Discrimination ratio is defined as the ratio of specified MTBF θ_o and the minimum acceptable MTBF θ, i.e., θ_o^o/θ, where θ = 1900 hours and θ_1 = 950 hours. The sequential test plan is predicted on the assumption that the times between failure of the LOX-30 system is exponentially distributed. As per test plan VIII an accept decision was reached at 161 7 hours without a relevant failure.

4. Because of the sample size and the number of failures accumulated during the test, the failure distribution of the LOX-30 system is unable, with a good degree of confidence, to be determined. Therefore, until further data is accumulated from other facilities and tests, it will be assumed that the LOX-30 system failure rate follows as exponential distribution.

Therefore the following:

$$R(t) = e^{-\frac{t}{\theta}}$$

where:

t = mission time (90 hours)
θ = minimum acceptable MTBF (950 hours)
R(t) = Probability of a failure free mission

$$R(90) = e^{-\frac{90}{950}}$$

$$R(90) = .90$$

The probability that the LOX-30 system will operate failure free for 90 continuous hours is 90%.

5. Although no relevant failures occurred during the test, corrective action was taken on the following failures:

a. During normal operation, it had been observed by the operators that adjustment of liquid levels in the column and storage tank had become increasingly difficult to stabilize. Hampson Meter readings had begun to read eratic and at times no reading at all. After an investigation of the Hampson Meter, it was discovered that the quick disconnects were bruised and cracked at the ends. Replacement of the quick disconnect was necessary. After replacement, normal readings were observed.

b. During normal operation absorber number two failed to switch over automatically or manually. During pre-reliability tests the solenoids of the electric heater and absorbers 1 and 2 were connected to a moist control air stream. After continued operation, the actuation chamber of the solenoid valves became rusty resulting in the plunger of the actuator to freeze up. To relieve this problem, the control air line was relocated from the wet air side of the adsorbers to the dry air side.

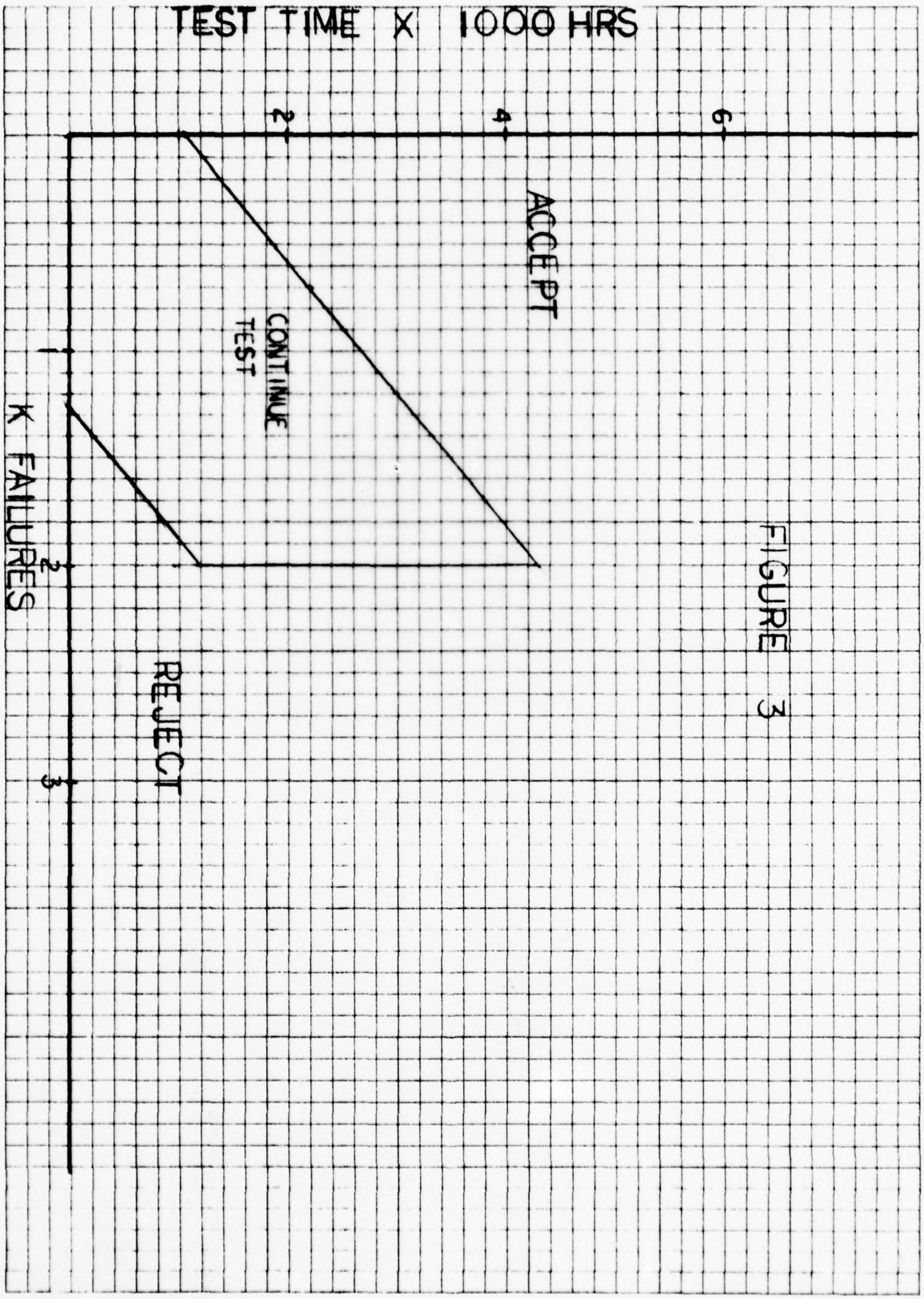

TEST TIME X 1000 HRS
2
4
6
ACCEPT
CONTINUE
TEST
REJECT
K FAILURES
1
2
3

FIGURE 3

In addition, both chambers were disassembled and lubricated. Engineering investigations concluded that lubrication of the plunger shaft will be required at 1500 hour intervals. A statistical analysis of the solenoid mechanisms are in Appendix E.

c. During normal operation, the adsorbers failed to switch automatically. After manually switching of the adsorbers was completed, a slight air leak was found at the fitting that houses the solenoid valve. After disassembly, it was discovered that the threads were stripped thus not permitting enough air pressure to flow into the assembly to allow adsorber switching. The cause for the leak was excessive tightening of the steel thread to an aluminum housing. Like joining metals of the assembly was recommended along with specified torque valves.

d. During normal operation, the discharge pipe connection between the air compressor and molecular sieve station vibrated excessively resulting in pipe fracture. Upon assembly of the LOX-30 unit air compressor, shipment of the proper dampner for the discharge pipe was never supplied. Electrical transducers were mounted on the pipe during post reliability tests and showed that the pipe vibrated at approximately 1660 Hz in the x, y and z direction. A vibration dampner at the compressor discharge pipe is necessary for proper plant operation.

I. OBSERVATION AND DEDUCTIONS.

From the data accumulated and from findings uncovered during the phase of study several observations/deductions may be made:

-- Although cryogenic systems have been in existence for many years, very little statistically significant reliability data is available on liquid oxygen systems and components.

-- Because of usual high cost and large size, liquid oxygen components are traditionally used at near their full capacity. Consequently, adequate derating is an important factor in cryogenic systems.

-- Data show very little field data available for cryogenic systems.

-- Little effort has been expended in the area of physics-of-failure and stress studies of these systems.

-- In-plant life tests are too short duration to yield any significant data for predicting the useful life and wear-out characteristics of cryogenic systems.

-- The survival cumulative distribution of most cryogenic systems is unknown. It is only assumed that their survival cumulative distribution follow those of complex system components.

It is only assumed that their life characteristics exhibit periods of "early life", "constant failure-rate", and "wear-out".

From a reliability, as well as a design engineer's viewpoint, all the points expressed are of interest. To the reliability engineer and those responsible for advancing reliability technology in cryogenic components, the last, is of most interest.

If survival cumulative distribution function could be identified with any degree of accuracy for each application of liquid oxygen or nitrogen components, decisions could be made on what is the optimum period to burn-in each component be replaced just before effects of wear-out become excessive, and how to design for optimizing the useful life period. Finding the survival cumulative distribution function, however, for cryogenic components is not a simple task.

J. CONCLUSIONS.

The LOX-30 liquid oxygen system satisfactorily completed the reliability tests meeting the requirements established in the test plans.

The LOX-30 system experienced four irrelevant failures, none of which caused any excessive down time for repair.

During operation of the LOX-30 system, it is imperative that no less than two operators be assigned for efficient plant operation.

After the LOX-30 system has reached its liquid oxygen production phase, monitoring of instruments is recommended every thirty minutes.

Contractor operational procedures and manuals were incomplete.

K. RECOMMENDATIONS.

Lubricate the electro-pneumatic solenoid actuation chamber of the valves on the molecular sieve skid at an assigned interval of 1500 hours.

Operational procedures for the LOX-30 system must be rewritten for efficient operation.

RELIABILITY TEST REPORT

MODULAR CRYOGENIC GENERATOR

APPENDIX A

WEEK	MON	TUES	WED	THURS	FRI	SAT	SUN	REMARKS
AUG 1 TO AUG 6	ADSORBER TIME 90MIN START 500GAL FILL 15:00		CH_4 13. PPM N_2O .6 PPM CO_2 11.PPM		TEST EH-2 500GAL FULL 16:00	1		CO_2 HIGH DUE TO TIME 1 TIME END 2099.7 7.71 GAL/HOUR
AUG 8 TO AUG 13				CH_4 21.5 PPM N_2O 1.6 PPM CO_2 11.PPM	TEST EH-2	1		N_2O & CO_2 HIGH TREND 1 TIME END 2212.7 6.93GAL/HR
AUG 15 TO AUG 20			CH_4 29.5 PPM N_2O 4.PPM CO_2 21.PPM 1		CH_4 26.PPM N_2O 1.4 PPM CO_2 12.PPM 1	END RELIABILITY TEST 1616.6HRS 2		TIME END 2326.6 1 SAMPLES HIGH DUE TO 90MIN CHANGE 6.87 GAL/HR 2 TOTAL COMPRESSOR RUNNING TIME 1732HRS

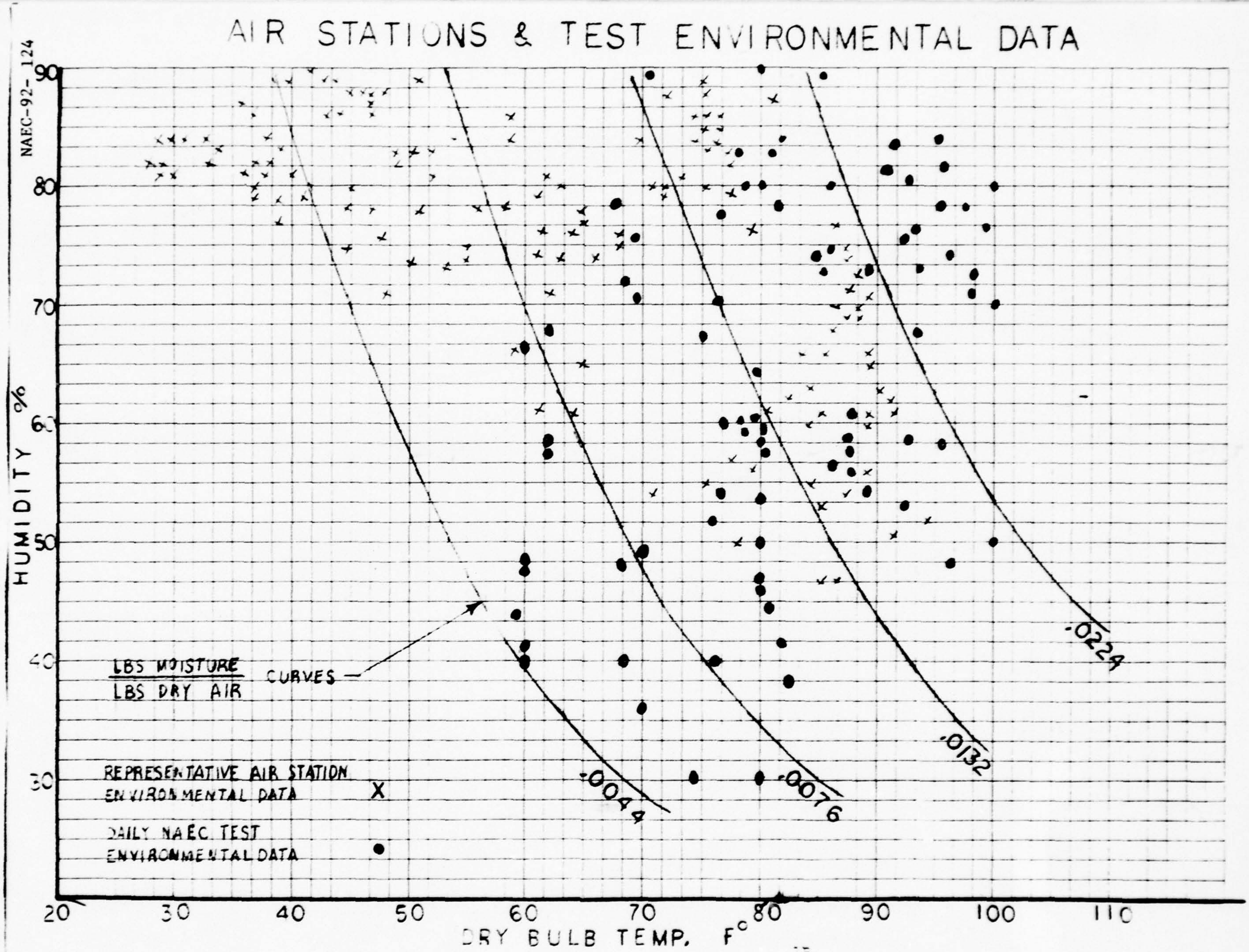
WEEK	MON	TUES	WED	THURS	FRI	SAT	SUN	REMARKS
JUNE 13 TO JUNE 19						1		TIME END 1381.3 1
JUNE 20 TO JUNE 26	MANUAL SW			CH_4 19. PPM N_2O .84 PPM CO_2 2.4 PPM	VALVE # 2 SOLONOID STUCK	1		1 1500 HR MAINTENANCE TIME END 1491.5
JUNE 27 TO JULY 2			CH_4 19. PPM N_2O .9 PPM CO_2 2.0 PPM	POWER LOSS 16:00 DISCONNECT TANK	RESTART 0530			TIME END 1594.2 7.18 GAL/HR
JULY 5 TO JULY 9		CH_4 17.5 PPM N_2O .94 PPM CO_2 12. PPM MACH. NOT STABLE						TIME END 1686.2 6.60 GAL/HR
JULY 11 TO JULY 16	1					2		1 PAX RIVER TRAINING 2 TIME END 1701.3
JULY 18 TO	1	START 500 GAL FILL 14:00		CH_4 13. PPM N_2O .76 PPM CO_2 9.0 PPM 2	TEST EH-2		TANK FULL 15:00 3.12 GAL/HR	1 START TWO WEEK RUN 2 CO_2 HIGH RESAMPLE 3 TANK & MACHINE
JULY 30		3 CH_4 13. PPM N_2O .76 PPM CO_2 3.3 PPM						TIME END 1984.8

WEEK	MON	TUES	WED	THURS	FRI	SAT	SUN	REMARKS
MARCH 28 TO APRIL 2	TIME 710.3 START		CH_4 17.5 PPM N_2O .54 PPM CO_2 1.0 PPM		TEST EH-2	TIME 825.1		
APRIL 4 TO APRIL 9			CH_4 18. PPM N_2O .40 PPM CO_2 .60 PPM		TEST EH-2	TIME END 940.6		LOX FLOW PATE 3.17 GAL/HR
APPIL 11 TO APRIL 16			CH_4 15.5 PPM N_2O .49 PPM CO_2 .79 PPM		TEST EH-2	TIME END 1060.9		FLOW 3.61 GAL/HR
APRIL 18 TO APPIL 23		WATER CHILL-ER DOWN				①		① TIME END 1093.1
APPIL 25 TO APRIL 30	MANUAL SW.	NO PURITY CH_4 14 PPM N_2O .28 PPM CO_2 13. PPM ①	VALVE STICK-ING	NO BED SW SYS. DOWN		TIME END 1150.7		① CO_2 HIGH DUE TO NO SWITCH. HIGH TIME ON BED FLOW 7.2 GAL/HR
MAY 2 TO MAY 8			CH_4 16.5 PPM N_2O .52 PPM CO_2 2.0 PPM	VALVE STIC-KING		① ②		① MANUAL SWITCH ② TIME END 1267.2
MAY 9 TO JUNE 12	①							① VALVE 677 SOLONOID THREADS STIPPED SYSTEM DOWN AT 1267.2

RELIABILITY TEST REPORT

MODULAR CRYOGENIC GENERATOR

APPENDIX B


AIR STATIONS & TEST ENVIRONMENTAL DATA
HUMIDITY %
90
80
70
60
50
40
30
20
30
40
50
60
70
80
90
100
110
DRY BULB TEMP. F°
LBS MOISTURE / LBS DRY AIR CURVES
.0044
.0076
.0132
.0224
REPRESENTATIVE AIR STATION ENVIRONMENTAL DATA X
DAILY NAEC TEST ENVIRONMENTAL DATA ●

RELIABILITY TEST REPORT

MODULAR CRYOGENIC GENERATOR

APPENDIX C

FAILURE REPORT

MODULAR CRYOGENIC OXYGEN GENERATOR

Failure No. 1 Date: 13 April 1977

Generator Ser. No. LOX-30 Elapsed Time Meter 1017.8

Identification of failed item:

Nomenclature QUICK DISCONNECT FITTINGS

Part No. 320-104 Serial No. ______

Mode of Operation when discovered: Normal liquid O_2 production.

Result of failure (abort, degraded, etc.): Incorrect liquid level indication.

Description of failure: Liquid level indication could not be maintained. Indicating liquid would rise out of the top of meter when connected.

Description of cause: Seat of disconnect was broken and cracked.

Action taken: Replaced quick disconnect with new ones.

Recommendation to prevent recurrence:

Categorization of failure (see paragraph II)

	Hours	No. of Personnel	No. of Manhours
Time for fault location	.2	1	.2
Time for repair	.4	1	.4
Time for checkout	.2	1	.2
Total	.8	1	.8

Total downtime (total time from failure to back in operation) ______

Report prepared by C.R. CORKUM
(Print)

FAILURE REPORT

MODULAR CRYOGENIC OXYGEN GENERATOR

Failure No. 2 Date: 28 April 1977

Generator Ser. No. LOX-30 Elapsed Time Meter 1151

Identification of failed item:

Nomenclature ELECTRO-PNEUMATIC SOLENOID VALVE

Part No. ______ Serial No. 62.35.50

Mode of Operation when discovered: Normal operating.

Result of failure (abort, degraded, etc.): System shut-down.

Description of failure: Adsorber #2 failed to switch automatically or manually.

Description of cause: During pre-test runs, the solenoids of the electric heater and adsorbers #1 & #2 were in a moist air stream causing corrosion.

Action taken: A snap ring made from wire was placed inside of rubber plunger. Plunger shaft lubricated every 1500 hrs. of operation. Failed solenoid valve tubing is in stream with dry air.

Recommendation to prevent recurrence: Lubrication of shaft every 1500 hrs. and re-route tubing from moist air stream to in stream dry air source.

Categorization of failure (see paragraph III)

	Hours	No. of Personnel	No. of Manhours
Time for fault location	1 hr.	1	1
Time for repair	.75	1	.75
Time for checkout	.50	1	.50
Total	2¼	1	2¼

Total downtime (total time from failure to back in operation) 4 hrs.

Report prepared by ROMAN FERRET
(Print)

FAILURE REPORT

MODULAR CRYOGENIC OXYGEN GENERATOR

Failure No. 3 Date: 9 May 1977

Generator Ser. No. LOX-30 Elapsed Time Meter 1570.2

Identification of failed item:

Nomenclature SOLENOID OPERATED AIR VALVE (TILLER PNEUMATIC)

Part No. ______ Serial No. 33.311.011

Mode of Operation when discovered: Normal operation.

Result of failure (abort, degraded, etc.): Had to change from automatic control to manual control to change adsorber #1 to #2.

Description of failure: Adsorber failed to change.

Description of cause: Fitting that houses the valve was stripped and leaked not allowing enough pressure into the actuation chamber.
Action taken: Remove valve for engineering study.

Recommendation to prevent recurrence: Avoid a steel fitting thread into an aluminum body.

Categorization of failure (see paragraph III)

	Hours	No. of Personnel	No. of Manhours
Time for fault location	.2	1	.2
Time for repair			
Time for checkout			
Total			

Total downtime (total time from failure to back in operation) ______

Report prepared by C.R. CORKUM
(Print)

FAILURE REPORT

MODULAR CRYOGENIC OXYGEN GENERATOR

Failure No. 4 Date: 18 July 1977

Generator Ser. No. LOX-30 Elapsed Time Meter 1705.3

Identification of failed item:

Nomenclature PIPE NIPPLE

Part No. ______ Serial No. ______

Mode of Operation when discovered: Normal O_2 operation.

Result of failure (abort, degraded, etc.): Plant shut-down.

Description of failure: Pipe nipple at the discharge end of the air compressor ruptured.

Description of cause: Rupture due to excessive vibration.

Action taken: Remove and replace nipple.

Recommendation to prevent recurrence: Install discharge piping as described in compressor manual. Still waiting for design change from manufacturer.

Categorization of failure (see paragraph III)

	Hours	No. of Personnel	No. of Manhours
Time for fault location	Immed-iate	1	Immediate
Time for repair	¼ hr.	1	¼ hr.
Time for checkout	5 min.	1	5 min.
Total	20	1	20

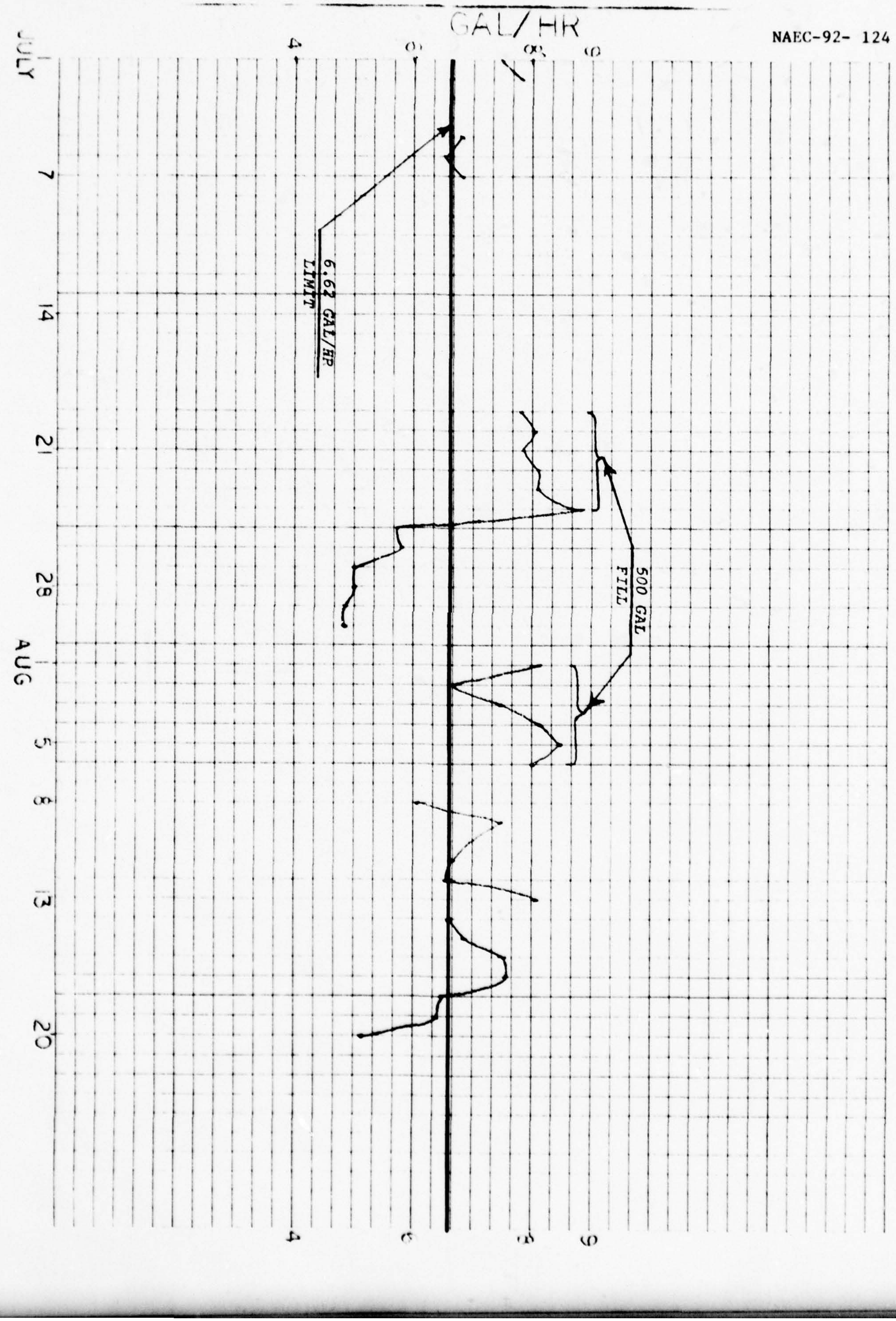
Total downtime (total time from failure to back in operation) 45 min.

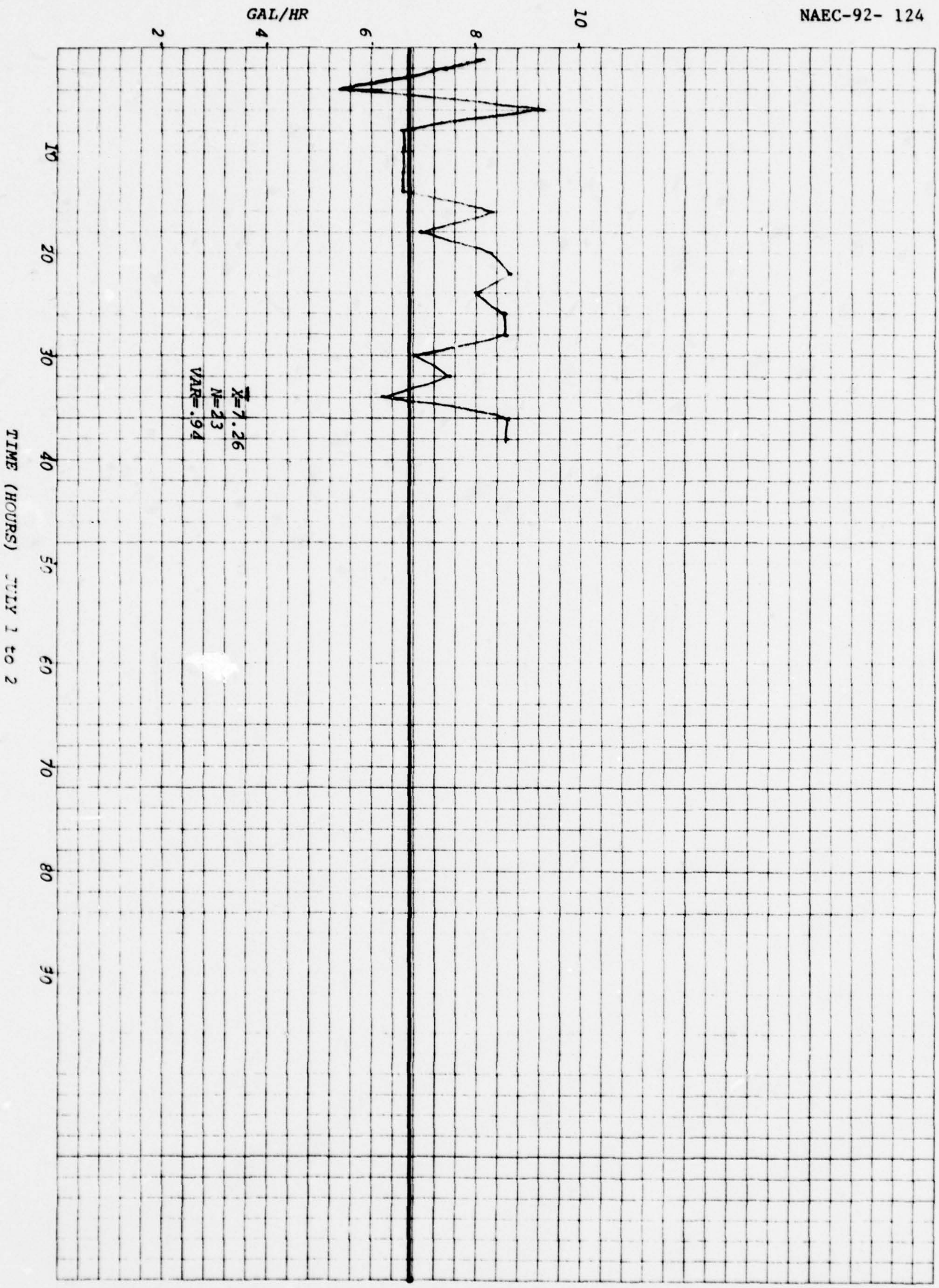
Report prepared by ROMAN FERRET
(Print)

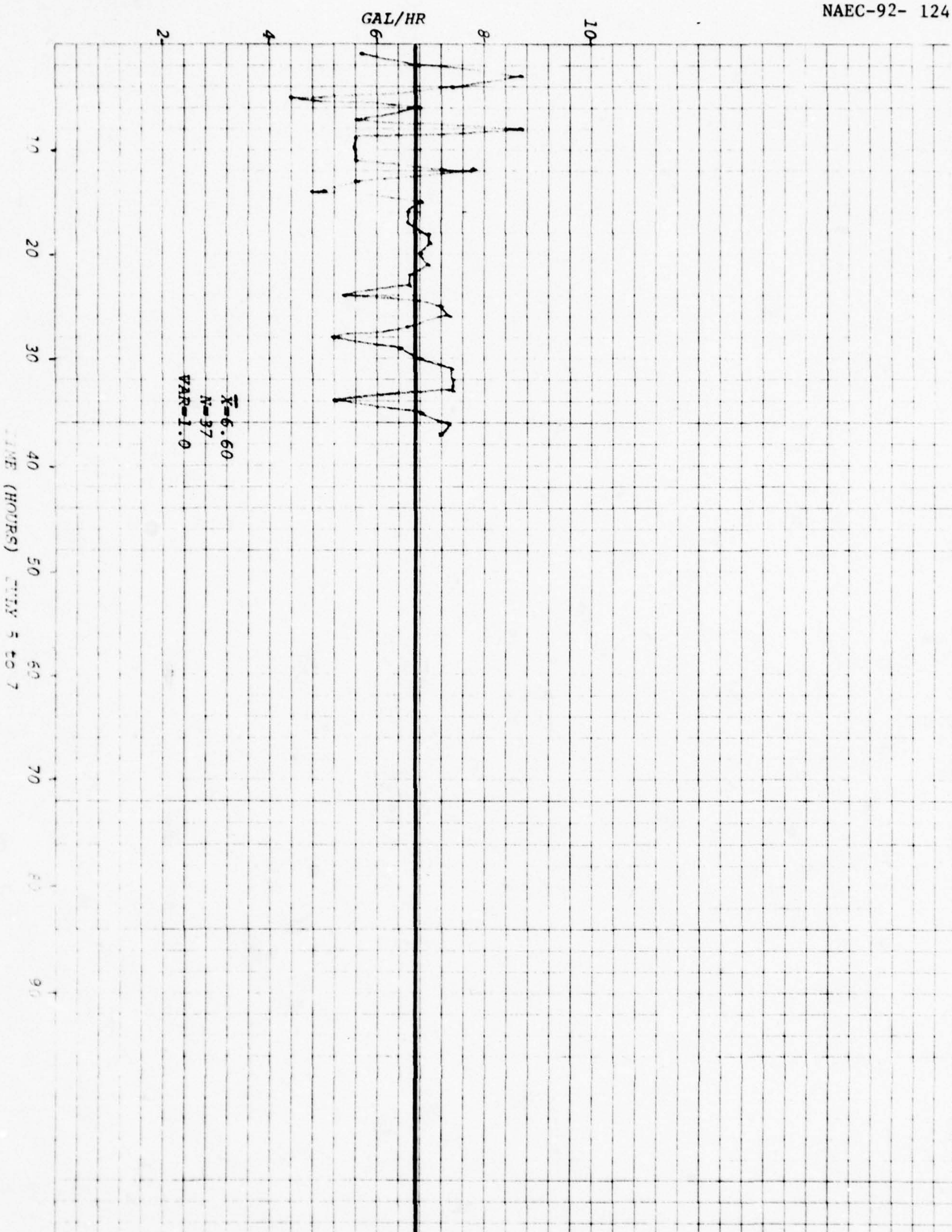
RELIABILITY TEST REPORT

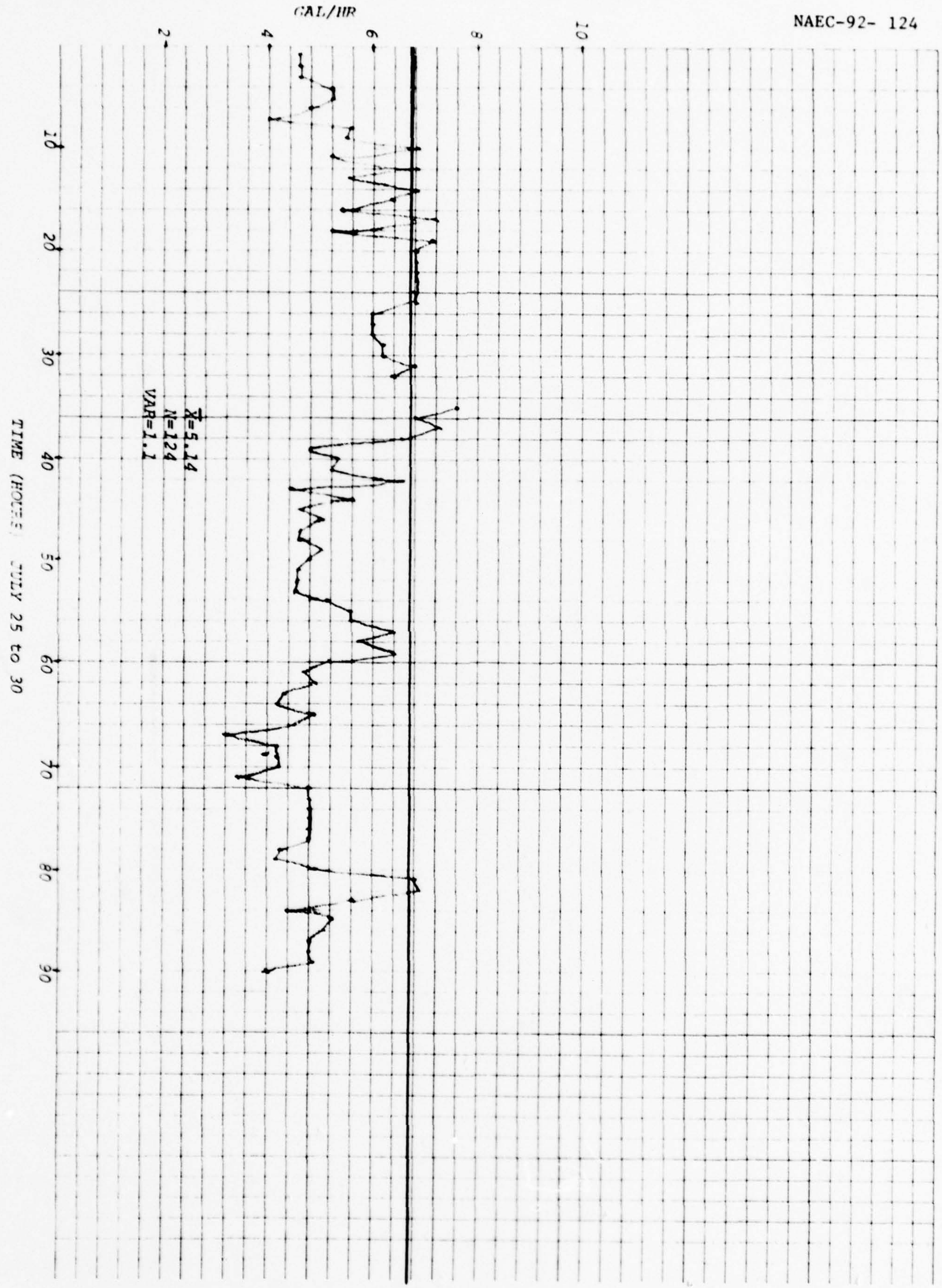
NODULAR CRYOGENIC GENERATOR

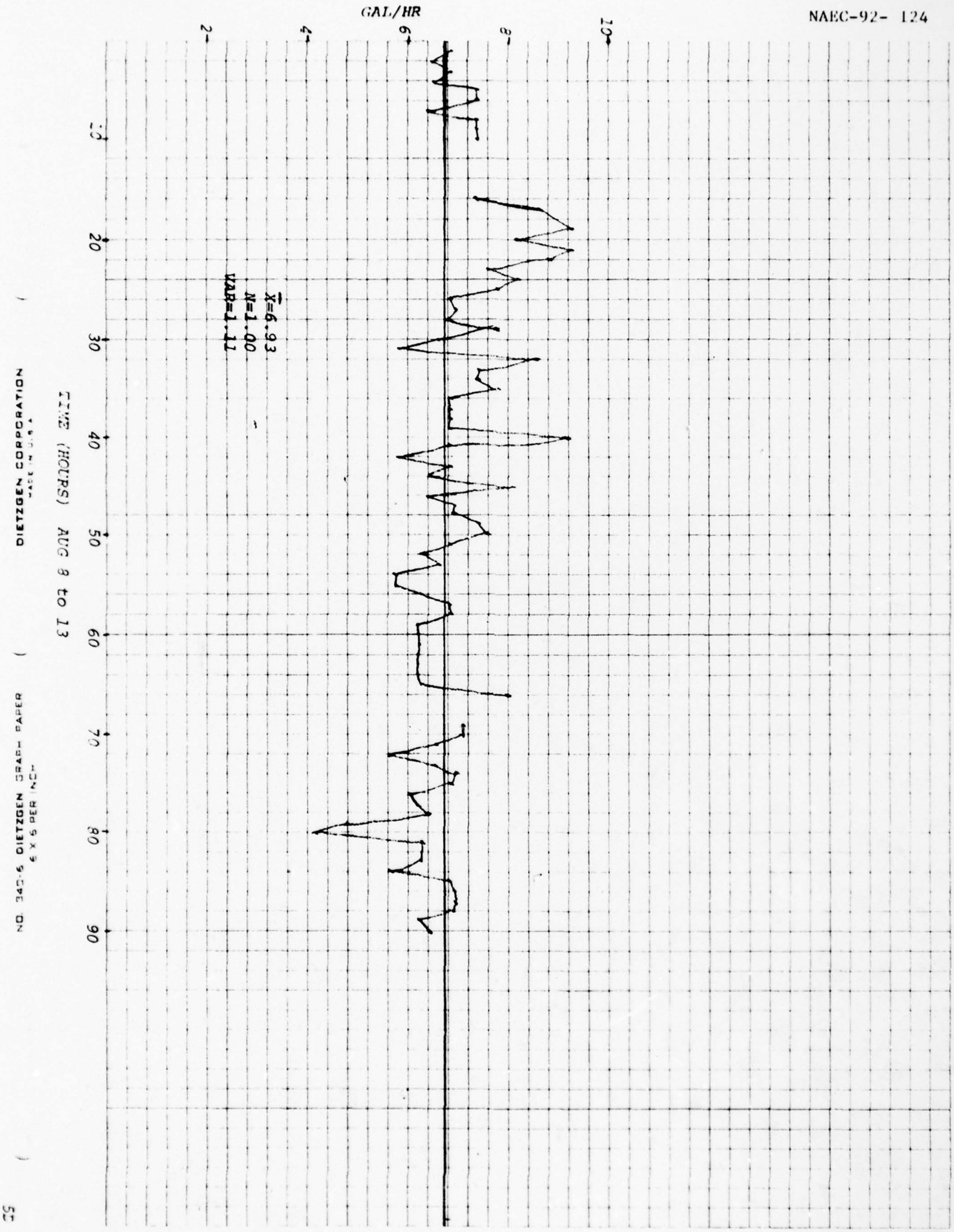
APPENDIX D

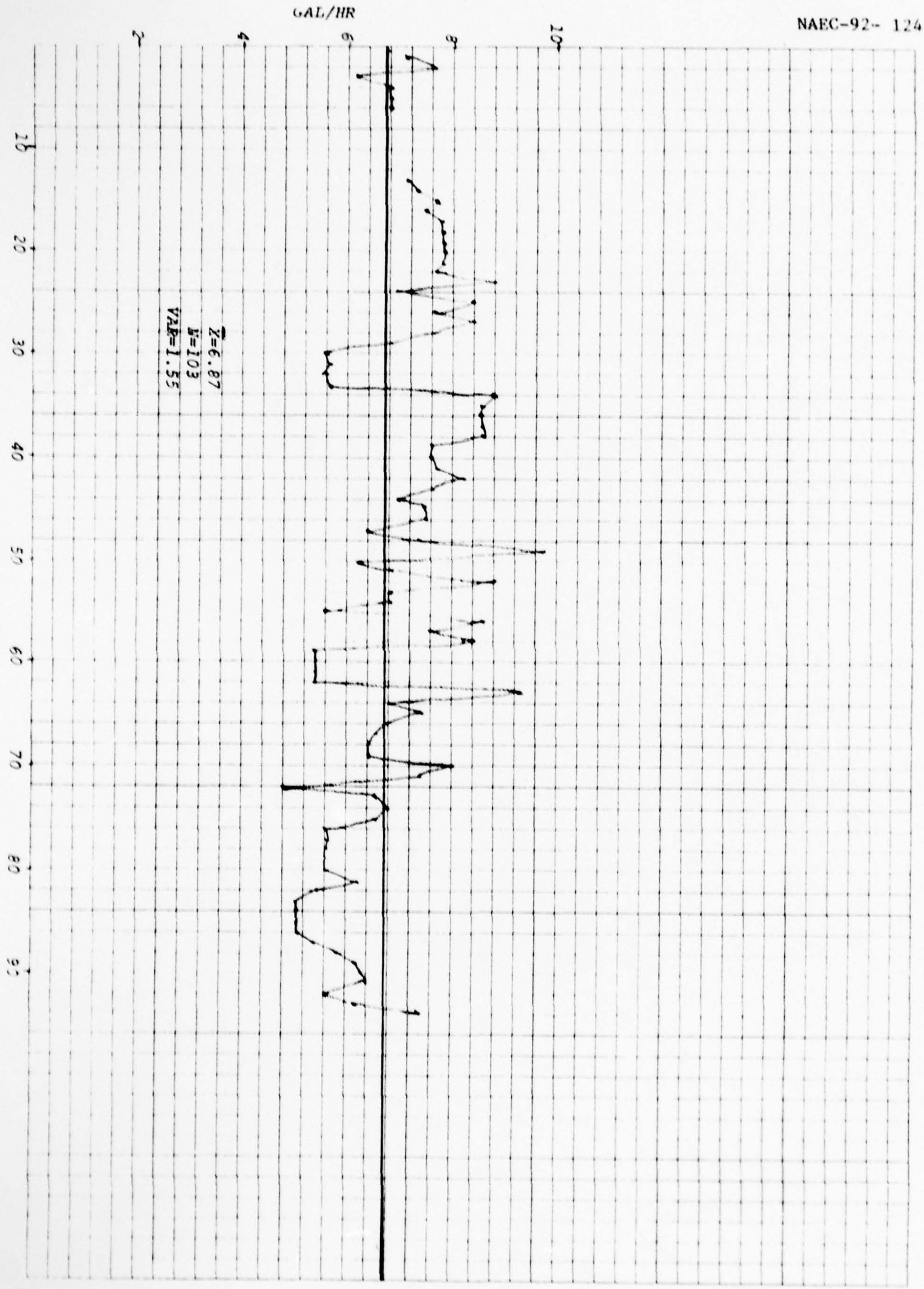

GAL/HR
4
6
8
9
JULY
7
14
21
28
AUG
5
8
13
20
6.62 GAL/HR
LIMIT
500 GAL
FILL


GAL/HR
2
4
6
8
10
10
20
30
40
50
60
70
80
90
$\bar{X}$=7.26
N=23
VAR=.94
TIME (HOURS) JULY 1 to 2


GAL/HR
2
4
6
8
10
10
20
30
40
50
60
70
TIME (HOURS) JULY 5 to 7
$\bar{X}$=6.60
N=37
VAR=1.0


GAL/HR
2
4
6
8
10
10
20
30
40
50
60
70
80
90
X̄=5.14
N=124
VAR=1.1
TIME (HOURS) JULY 25 to 30


GAL/HR
2
4
6
8
10
10
20
30
40
50
60
70
80
90
$\bar{X}$=6.93
N=1.00
VAR=1.11
TIME (HOURS) AUG 8 to 13
DIETZGEN CORPORATION
NO. 340-5 DIETZGEN GRAPH PAPER
5 X 5 PER INCH


GAL/HR
2
4
6
8
10
10
20
30
40
50
60
70
80
90
TIME (HOURS)
$\bar{X}$=6.87
N=103
VAR=1.55

JULY 1 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100										
0200										
0300										
0400										
0500										
0600										
0700										
0800										
0900	92	8.17	99.6							
1000	96	7.58	99.6							
1100	99	5.59	99.6							
1200	99	9.38	99.5							
1300	98	6.42	99.2							
1400	96	6.42	99.2							
1500	98	6.42	99.4							
1600	99	6.42	99.2							
1700	98	8.17	99.3							
1800	98	7.00	99.25							
1900	97	8.10	98.8							
2000	92	8.68	99.0							
2100	94	8.00	99.0							
2200	82	8.53	98.7							
2300	79	8.53	98.9							
2400	80	6.82	98.9							

JULY 2 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	78	7.40	98.6							
0200	80	7.40	98.9							
0300	76	7.97	99.1							
0400	76	7.94	99.1							
0500	76	6.25	99.12							
0600	76	8.55	99.25							
0700	78	8.55	99.3							
0800										
0900										
1000										
1100										
1200										
1300										
1400										
1500										
1600										
1700										
1800										
1900										
2000										
2100										
2200										
2300										
2400										

JULY 5 1977

	TIME	AMBIENT TEMP	GAL/HR	PURITY							
	0100										
	0200										
	0300										
	0400										
	0500										
	0600										
	0700										
	0800										
	0900										
	1000										
	1100										
	1200										
$\overline{x} = 6.61$	1300	104		99.95							
	1400	105		99.95							
	1500	100		99.95							
	1600	102		99.95							
	1700	102	5.85	99.9	1						
	1800	100	6.71	99.85	2						
	1900	97	8.73	99.85	3						
	2000	94	7.51	99.9	4						
	2100	90	4.29	99.9	5						
	2200	90	6.89	99.9	6						
	2300	88	5.73	99.95	7						
	2400	85	8.59	99.95	8						

JULY 6 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY	
0100	84	5.70	99.75	9
0200	82	5.70	99.85	10
0300	82	5.70	99.8	11
0400	80	7.94	99.89	12
0500	78	5.68	99.9	13
0600	79	4.53	99.9	14
0700	82	6.86	100	15
0800	88	6.33	100	16
0900	93	6.41	100	17
1000	94	7.00	99.8	18
1100	95	7.00	99.99	19
1200	96	6.74	99.99	20
1300	95	7.04	99.95	21
1400	98	6.45	99.95	22
1500	100	6.48	99.95	23
1600	98	5.56	99.95	24
1700	90	7.24	99.9	25
1800	84	7.69	99.85	26
1900	82	6.54	99.85	27
2000	80	5.19	99.9	28
2100	78	6.33	99.9	29
2200	80	6.89	99.92	30
2300	78	7.48	99.95	31
2400	70	7.49	99.95	32

JULY 7 1977

$Y = 6.38 + 01x$

$r^2 = .02$

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	80	7.49	99.99	33						
0200	76	5.15	99.99	34						
0300	74	6.86	99.99	35						
0400	76	7.44	99.99	36						
0500	74	7.44	99.99	37						
0600										
0700										
0800										
0900										
1000										
1100										
1200										
1300										
1400										
1500										
1600										
1700										
1800										
1900										
2000										
2100										
2200										
2300										
2400										

JULY 19 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100										
0200										
0300										
0400										
0500										
0600										
0700										
0800										
0900										
1000										
1100										
1200										
1300										
1400	103	7.97	98.6							
1500	109	7.12	97.6							
1600	109	7.12	96.4							
1700	108	6.52	95.8							
1800	109	7.63	96.55							
1900	100	7.00	96.6							
2000	97	7.53	97.0							
2100	97	6.33	96.65							
2200	96	6.84	97.45							
2300	92	7.48	97.1							
2400	92	7.47	97.75							

JULY 20 1977

	TIME	AMBIENT TEMP	GAL/HR	PURITY							
	0100										
	0200										
	0300										
	0400										
	0500										
	0600										
	0700										
	0800										
	0900										
	1000										
	1100										
	1200										
	1300										
Start 500 Gal fill	1400	96	8.02	100	1						
	1500	98	8.02	100	2						
	1600	98	8.03	100	3						
	1700	97	7.73	100	4						
	1800	97	8.29	100	5						
	1900	95	7.99	100	6						
	2000	94	7.70	100	7						
	2100	90	7.98	100	8						
	2200	88	7.98	100	9						
	2300	86	7.96	100	10						
	2400	84	7.96	100	11						

JULY 21 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY	
0100	86	7.39	100	12
0200	82	7.96	100	13
0300	81	7.96	100	14
0400	82	7.96	100	15
0500	81	7.96	100	16
0600	82	7.96	100	17
0700	82	7.98	99.9	18
0800	90	7.99	100	19
0900	98	8.03	100	20
1000	100	8.05	100	21
1100	103	8.05	100	22
1200	106	8.36	99.9	23
1300	110	8.36	99.9	24
1400	110	8.05	99.9	25
1500	113	7.75	100	26
1600	112	7.75	100	27
1700	112	8.06	100	28
1800	107	7.45	100	29
1900	104	7.32	100	30
2000	99	7.42	100	31
2100	98	7.41	100	32
2200	88	7.39	100	33
2300	86	7.39	100	34
2400	86	7.39	100	35

JULY 22 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY								
0100	86	7.39	160	36							
0200	86	7.39	160	37							
0300	84	7.39	160	38							
0400	84	7.39	160	39							
0500	84	7.40	160	40							
0600	84	7.40	160	41							
0700	84	7.40	160	42							
0800	87	7.85	160	43							
0900	89	8.02	160	44							
1000	90	8.31	160	45							
1100	91	8.31	160	46							
1200	92	8.62	160	47							
1300	92	8.33	160	48							
1400	94	8.05	160	49							
1500	94	8.28	160	50							
1600	94	7.99	160	51							
1700	94	8.57	160	52							
1800	92	8.27	160	53							
1900	90	8.55	160	54							
2000	90	7.96	99.95	55							
2100	84	8.53	99.95	56							
2200	82	8.53	99.95	57							
2300	79	8.53	99.95	58							
2400	79	8.53	99.95	59							

JULY 23 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY	
0100	72	8.49	99.49	60
0200	70	8.49	99.49	61
0300	68	8.49	99.49	62
0400	66	8.49	99.49	63
0500	66	8.49	99.49	64
0600	66	8.49	99.49	65
0700	68	6.23	99.49	66
0800	69	7.97	100	67
0900	84	7.70	100	68
1000	86	7.43	100	69
1100	86	8.31	100	70
1200	89	8.02	100	71
1300	90	7.73	100	72
1400	90	8.02	99.95	73
1500	92	7.99	100	74
1600	95	7.99	100	75
1700	95	7.99	100	76
1800	93	7.98	100	77
1900	90	7.98	100	78
2000	84	7.96	100	79
2100	78	7.94	100	80
2200	76	7.94	100	81
2300	78	8.51	100	82
2400	78	7.94	100	83

JULY 24 1977

	TIME	AMBIENT TEMP	GAL/HR	PURITY							
	0100	78	7.94	100							
	0200	76	7.93	100							
	0300	72	7.93	100							
	0400	72	7.93	100							
	0500	72	7.93	100							
	0600	72	7.93	100							
	0700	75	8.80	99.95							
	0800	84	9.70	100							
	0900	89	10.61	100							
	1000	93	9.48	99.95							
	1100	94	10.08	100							
	1200	97	9.51	99.95							
	1300	95	9.79	99.95							
	1400	98	9.80	99.9							
500 Gallon Tank	1500	99	9.77	99.9							
Finish	1600	97	13.33	99.95							
	1700	94	12.68	100							
	1800	88	11.46	100							
	1900	84	11.46	100							
	2000	80	10.84	100							
	2100	80	10.24	100							
	2200	78	10.81	100							
	2300	78	10.81	100							
	2400	78	10.81	100							

JULY 25, 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	78	4.57	100							
0200	78	4.57	100							
0300	78	4.57	100							
0400	78	5.14	100							
0500	78	5.14	100							
0600	80	4.57	100							
0700	80	4.00	100							
0800	83	5.74	99.99							
0900	84	5.74	99.99							
1000	86	6.89	99.99							
1100	87	5.17	99.89							
1200	85	6.89	100							
1300	90	5.47	100							
1400	88	6.65	100							
1500	88	6.36	100							
1600	84	5.46	100							
1700	82	7.14	100							
1800	82	5.71	100							
1900	80	7.14	100							
2000	82	5.71	100							
2100	82	6.86	100							
2200	80	6.86	100							
2300	81	6.82	100							
2400	81	6.82	100							

JULY 26 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	81	6.82	100							
0200	78	6.82	100							
0300	76	5.66	100							
0400	72	5.66	100							
0500	72	5.66	100							
0600	69	6.22	100							
0700	72	6.22	100							
0800	75	6.86	100							
0900	76	6.32	100							
1000	80	-	99.9							
1100	82	-	99.9							
1200	84	7.54	99.9							
1300	86	6.71	99.9							
1400	88	7.25	99.6							
1500	88	6.42	99.8							
1600	87	4.60	99.9							
1700	87	5.21	99.95							
1800	88	5.17	99.9							
1900	85	6.57	99.9							
2000	82	4.26	99.9							
2100	74	5.66	99.99							
2200	73	4.53	99.98							
2300	70	5.09	99.98							
2400	68	4.53	99.98							

JULY 27 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	66	4.53	99.89							
0200	66	5.09	99.89							
0300	64	4.81	99.89							
0400	62	4.48	99.89							
0500	62	4.48	99.89							
0600	58	4.48	99.89							
0700	64	5.09	99.89							
0800	72	5.71	99.9							
0900	78	5.76	99.9							
1000	80	6.36	99.9							
1100	84	5.83	99.9							
1200	85	6.36	99.9							
1300	86	5.27	99.9							
1400	88	4.63	99.5							
1500	88	4.92	99.7							
1600	87	4.34	99.95							
1700	86	4.04	99.99							
1800	87	4.89	99.99							
1900	82	4.57	99.99							
2000	79	3.70	99.85							
2100	70	4.53	99.89							
2200	68	4.53	99.9							
2300	67	4.53	99.9							
2400	66	3.92	99.89							

JULY 28 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	63	5.04	99.89							
0200	62	5.04	99.89							
0300	62	5.04	99.89							
0400	60	5.04	99.89							
0500	60	5.04	99.89							
0600	58	5.04	99.89							
0700	62	4.48	99.89							
0800	72	4.55	99.89							
0900	80	5.18	99.9							
1000	82	6.94	99.9							
1100	88	6.96	99.95							
1200	88	5.83	99.95							
1300	88	4.38	99.8							
1400	86	5.21	99.8							
1500	88	5.18	99.8							
1600	89	4.62	99.9							
1700	85	4.62	99.9							
1800	87	4.88	99.95							
1900	82	4.00	99.95							
2000	79	5.12	99.95							
2100	74	4.53	99.9							
2200	72	4.53	99.9							
2300	70	4.53	99.9							
2400	68	4.53	99.9							

JULY 29 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	68	4.53	99.89							
0200	67	3.96	99.89							
0300	66	3.96	99.89							
0400	63	3.96	99.89							
0500	62	3.96	99.89							
0600	61	3.96	99.89							
0700	64	5.66	99.9							
0800	70	5.12	99.9							
0900	84	4.63	99.95							
1000	84	4.63	100							
1100	85	5.50	99.98							
1200	90	7.00	99.9							
1300	92	6.36	99.9							
1400	92	5.48	99.95							
1500	94	5.50	99.95							
1600	94	5.21	99.9							
1700	92	5.21	99.95							
1800	88	5.74	99.95							
1900	86	4.59	99.95							
2000	84	5.14	99.95							
2100	82	4.55	99.9							
2200	79	4.55	99.9							
2300	81	-	99.9							
2400	80	4.53	99.9							

JULY 30 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	80	4.53	99.99							
0200	78	3.96	99.99							
0300	78	4.53	99.99							
0400	78	4.53	99.99							
0500	76	4.53	99.99							
0600	74	4.53	99.99							
0700	76	4.53	99.99							
0800										
0900										
1000										
1100										
1200										
1300										
1400										
1500										
1600										
1700										
1800										
1900										
2000										
2100										
2200										
2300										
2400										

AUG 1 1977

	TIME	AMBIENT TEMP	GAL/HR	PURITY							
	0100										
	0200										
	0300										
	0400										
	0500										
	0600										
	0700										
	0800										
	0900										
	1000										
	1100										
	1200	95									
	1300	96									
	1400	98									
Start 500 Gal Fill	1500	92	8.25	99.8	1						
	1600	88	9.13	99.55	2						
	1700	80	8.56	99.6	3						
	1800	75	7.42	99.5	4						
	1900	78	8.84	99.55	5						
	2000	77	8.61	99.6	6						
	2100	78	7.66	99.7	7						
	2200	78	7.69	99.78	8						
	2300	77	7.69	99.75	9						
	2400	78	7.69	99.7	10						

AUG 2 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY	
0100		7.70	99.7	11
0200		7.70	99.7	12
0300		6.00	99.9	13
0400		6.00	99.7	14
0500		6.00	99.7	15
0600	73	6.00	99.7	16
0700	70	6.86	99.7	17
0800	76	6.86	99.7	18
0900	82	6.87	99.8	19
1000	88	6.89	99.8	20
1100	90	6.88	99.85	21
1200	92	7.18	99.8	22
1300	93	6.90	99.8	23
1400	95	6.92	99.9	24
1500	96	6.33	99.9	25
1600	96	6.32	99.9	26
1700	98	6.33	99.95	27
1800	96	6.31	99.85	28
1900	90	6.30	99.85	29
2000	86	6.30	99.8	30
2100	81	6.30	99.8	31
2200	80	6.29	99.8	32
2300	78	6.29	99.8	33
2400	78	6.29	99.8	34

AUG 3 1977

	TIME	AMBIENT TEMP	GAL/HR	PURITY							
	0100	78	6.28	99.85		35					
	0200	77	6.28	99.85		36					
	0300	75	6.28	99.85		37					
	0400	74	6.28	99.85		38					
	0500	73	6.28	99.85		39					
	0600	74	6.28	99.85		40					
	0700	76	6.85	99.85		41					
	0800	79	6.86	99.85		42					
	0900	80	6.87	99.9		43					
Samples	1000	84	6.87	99.85		44					
Samples	1100	86	6.87	99.9		45					
	1200	78	9.15	99.9		46					
	1300	78	9.13	99.9		47					
	1400	80	8.56	99.9		48					
	1500	82	8.56	99.9		49					
	1600	82	8.56	99.9		50					
	1700	80	8.56	99.95		51					
	1800	82	8.86	99.95		52					
	1900	80	8.01	99.95		53					
	2000	78	8.01	99.95		54					
	2100	78	8.01	99.98		55					
	2200	78	8.01	99.99		56					
	2300	78	8.01	99.95		57					
	2400	78	7.98	99.99		58					

AUG 4 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	76	7.98	99.99	59						
0200	76	8.56	99.99	60						
0300	76	8.45	99.99	61						
0400	76	8.45	99.99	62						
0500	76	8.45	99.99	63						
0600	76	8.45	99.99	64						
0700	76	8.45	99.9	65						
0800	80	8.28	99.9	66						
0900	84	8.60	99.9	67						
1000	88	8.34	99.9	68						
1100	92	8.65	99.99	69						
1200	96	8.65	99.99	70						
1300	98	8.38	99.99	71						
1400	102	8.38	99.9	72						
1500	102	8.07	99.9	73						
1600	104	8.07	99.9	74						
1700	101	8.65	100	75						
1800	97	8.65	100	76						
1900	96	8.04	99.9	77						
2000	90	8.03	99.9	78						
2100	86	8.02	99.99	79						
2200	84	8.01	99.95	80						
2300	84	8.01	99.95	81						
2400	82	8.01	99.95	82						

AUG 5 1977

	TIME	AMBIENT TEMP	GAL/HR	PURITY							
	0100	82	8.01	99.9	83						
	0200	79	8.01	99.9	84						
	0300	79	8.01	99.9	85						
	0400	79	8.01	99.9	86						
	0500	79	8.01	99.9	87						
	0600	78	8.01	99.9	88						
	0700	80	8.56	99.9	89						
	0800	83	8.60	99.9	90						
	0900	90	8.63	99.9	91						
	1000	94	8.67	99.9	92						
	1100	97	8.69	99.9	93						
	1200	99	8.69	99.9	94						
	1300	102	8.99	99.95	95						
	1400	98	8.96	99.95	96						
	1500	102	8.96	99.95	97						
Frost detected	1600	102	8.96	99.9	98						
500 Gal Filled	1700	102	8.94	99.9	99						
	1800	100	8.94	99.9							
	1900	97	8.91	99.9							
	2000	92	8.61	99.9							
	2100	87	8.32	99.9							
	2200	87	8.02	99.9							
	2300	88	8.02	99.9							
	2400	88	8.02	99.9							

AUG .6 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	87	8.02	99.85							
0200	86	8.01	99.99							
0300	85	8.01	99.8							
0400	86	8.01	99.8							
0500										
0600										
0700										
0800										
0900										
1000										
1100										
1200										
1300										
1400										
1500										
1600										
1700										
1800										
1900										
2000										
2100										
2200										
2300										
2400										

AUG 8 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY
0100			
0200			
0300			
0400			
0500			
0600			
0700			
0800			
0900			
1000			
1100			
1200			
1300			
1400			
1500			
1600			
1700	99	6.74	99.8
1800	100	6.42	99.45
1900	96	6.65	99.55
2000	92	6.33	99.5
2100	88	7.47	99.4
2200	88	7.47	99.3
2300	87	6.28	99.3
2400	84	7.43	99.3

AUG 9 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY
0100	85	7.43	99.2
0200	85	7.43	99.2
0300	-	-	-
0400	-	-	-
0500	-	-	-
0600	-	-	-
0700	-	-	-
0800	86	7.48	99.0
0900	91	8.70	-
1000	93	9.33	98.8
1100	96	8.17	98.6
1200	97	9.33	97.0
1300	97	8.75	98.1
1400	98	7.58	98.6
1500	98	8.12	98.5
1600	98	7.87	98.6
1700	96	6.71	98.65
1800	93	6.94	98.85
1900	90	6.63	99.05
2000	87	7.75	98.3
2100	90	6.28	98.45
2200	89	5.71	97.3
2300	87	8.57	97.9
2400	89	7.43	97.3

AUG 10 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	86	7.39	95.6							
0200	69	7.96	97.2							
0300	67	6.82	98.2							
0400	67	6.82	97.5							
0500	66	6.82	98.5							
0600	72	6.82	99.6							
0700	79	9.10	99.6							
0800	79	6.82	99.5							
0900	82	5.71	99.5							
1000	85	6.89	99.79							
1100	86	6.28	99.6							
1200	85	8.04	99.55							
1300	86	6.33	99.8							
1400	87	6.92	99.75							
1500	91	6.94	99.7							
1600	91	7.52	99.9							
1700	92	7.83	99.85							
1800	92	6.92	99.7							
1900	89	6.32	99.8							
2000	85	6.57	99.8							
2100	84	5.71	99.8							
2200	83	5.68	99.85							
2300	84	6.28	99.82							
2400	81	6.86	99.85							

AUG 11 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY
0100	87	6.86	99.85
0200	74	6.28	99.86
0300	73	6.28	99.88
0400	74	6.25	99.88
0500	79	6.25	99.88
0600	77	6.25	99.88
0700	83	6.28	99.85
0800	86	6.32	99.9
0900	86	8.04	99.85
1000	91	-	99.9
1100	94	-	99.9
1200	97	7.04	99.9
1300	99	7.04	99.9
1400	98	6.42	99.9
1500	99	5.57	99.89
1600	99	6.42	99.8
1700	94	7.00	99.85
1800	98	6.74	99.95
1900	95	6.07	99.9
2000	90	6.04	99.9
2100	90	6.32	99.99
2200	88	4.59	99.9
2300	87	4.02	99.9
2400	85	6.28	99.99

AUG .12 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	90	6.29	99.99							
0200	73	5.71	99.99							
0300	75	6.86	99.8							
0400	75	6.86	99.92							
0500	75	6.86	99.8							
0600	73	6.82	99.8							
0700	78	6.25	99.85							
0800	83	6.28	99.9							
0900	88	6.36	99.9							
1000	92	6.36	99.75							
1100	96	8.17	99.65							
1200	97	7.00	99.5							
1300	97	7.29	99.1							
1400	93	7.00	99.5							
1500	93	6.94	99.55							
1600	90	7.04	99.35							
1700	91	6.63	99.2							
1800	91	7.48	99.2							
1900	90	8.62	99.2							
2000	88	8.04	99.3							
2100	88	-	98.0							
2200	88	-	96.0							
2300	84	-	96.0							
2400	84	5.71	95.0							

AUG 13 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY
0100	86	11.43	95.0
0200	84	12.57	97.8
0300	80	6.25	98.9
0400	80	6.25	99.3
0500	80	6.25	99.5
0600	80	5.71	99.6
0700			
0800			
0900			
1000			
1100			
1200			
1300			
1400			
1500			
1600			
1700			
1800			
1900			
2000			
2100			
2200			
2300			
2400			

AUG 15 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100										
0200										
0300										
0400										
0500										
0600										
0700										
0800										
0900										
1000										
1100										
1200										
1300										
1400										
1500										
1600										
1700	94	6.92	-							
1800	94	6.33	-							
1900	85	7.19	98.6							
2000	79	7.72	98.65							
2100	75	6.25	98.7							
2200	74	6.79	98.4							
2300	71	6.79	98.6							
2400	71	6.79	96.0							

AUG 16 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY
0100	-		
0200	-		
0300	-		
0400	-		
0500	-		
0600	66	-	98.5
0700	67	7.07	99.2
0800	69	7.40	99.45
0900	74	7.73	99.5
1000	77	7.49	99.65
1100	78	7.82	99.6
1200	81	7.83	99.6
1300	81	7.83	99.7
1400	82	7.89	99.6
1500	80	7.80	99.6
1600	-	-	-
1700	80	8.70	99.7
1800	80	6.91	Cul
1900	78	8.36	98.1
2000	78	7.75	97.4
2100	77	6.86	96.7
2200	76	5.70	95.7
2300	76	5.83	95.9
2400	75	5.70	96.8

AUG 17 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	-	5.71	97							
0200	-	8.88	98.0							
0300	-	8.59	98.5							
0400	-	8.59	98.9							
0500	-	8.59	98.7							
0600	77	8.59	99.2							
0700	77	7.48	99.25							
0800	78	7.48	99.0							
0900	80	7.53	99.1							
1000	84	8.11	99.0							
1100	84	7.55	99.1							
1200	80	6.89	99.5							
1300	80	7.51	99.5							
1400	82	7.53	99.5							
1500	82	6.34	99.6							
1600	84	7.44	99.5							
1700	82	9.79	99.6							
1800	84	6.28	99.7							
1900	84	6.86	99.5							
2000	83	8.59	99.4							
2100	83	6.86	99.6							
2200	83	6.86	99.6							
2300	82	5.70	99.7							
2400	81	8.51	99.65							

AUG 18 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	-	7.36	99.55							
0200	-	8.49	99.75							
0300	-	5.66	99.8							
0400	-	5.66	99.8							
0500	-	5.66	99.8							
0600	62	5.66	99.8							
0700	62	9.05	99.7							
0800	63	6.79	99.5							
0900	65	7.39	99.8							
1000	67	6.86	99.85							
1100	70	6.57	99.9							
1200	72	6.32	99.9							
1300	73	6.32	99.9							
1400	73	8.04	99.9							
1500	74	7.47	99.9							
1600	74	4.90	99.85							
1700	74	6.33	99.85							
1800	74	6.61	99.8							
1900	72	6.57	99.8							
2000	69	5.66	99.8							
2100	64	5.66	99.7							
2200	62	5.66	99.8							
2300	61	5.66	99.7							
2400	60	5.60	99.75							

AUG 19 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	—	6.15	99.8							
0200	—	5.59	99.8							
0300	—	5.04	99.85							
0400	—	5.04	99.88							
0500	—	5.04	99.8							
0600	52	5.04	99.9							
0700	54	5.59	99.85							
0800	59	6.15	99.9							
0900	65	6.25	99.95							
1000	69	—	99.9							
1100	71	—	99.95							
1200	72	—	99.9							
1300	72	5.73	99.9							
1400	72	6.32	99.6							
1500	72	7.48	99.9							
1600	72	7.48	99.9							
1700	72	6.57	99.95							
1800	70	6.86	99.9							
1900	69	7.11	99.75							
2000	67	6.80	99.7							
2100	66	7.93	99.6							
2200	66	4.55	99.6							
2300	66	6.22	99.65							
2400	66	6.79	99.50							

AUG 19 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY
0100	-	6.15	99.8
0200	-	5.59	99.8
0300	-	5.04	99.85
0400	-	5.04	99.88
0500	-	5.04	99.8
0600	52	5.04	99.9
0700	54	5.59	99.85
0800	59	6.15	99.9
0900	65	6.25	99.95
1000	69	-	99.9
1100	71	-	99.95
1200	72	-	99.9
1300	72	5.73	99.9
1400	72	6.32	99.6
1500	72	7.48	99.9
1600	72	7.48	99.9
1700	72	6.57	99.95
1800	70	6.86	99.9
1900	69	7.11	99.75
2000	67	6.80	99.7
2100	66	7.93	99.6
2200	66	4.55	99.6
2300	66	6.22	99.65
2400	66	6.79	99.50

AUG 20 1977

TIME	AMBIENT TEMP	GAL/HR	PURITY							
0100	-	5.65	99.3							
0200	-	5.64	99.7							
0300	-	4.46	99.65							
0400	-	4.45	99.6							
0500										
0600										
0700										
0800										
0900										
1000										
1100										
1200										
1300										
1400										
1500										
1600										
1700										
1800										
1900										
2000										
2100										
2200										
2300										
2400										

RELIABILITY TEST REPORT

MODULAR CRYOGENIC GENERATOR

APPENDIX E

ANALYSIS FOR THE ELECTRO-PNEUMATIC

SOLENOIDS OF THE LOX-30 SYSTEM

ANALYSIS FOR THE ELECTRO-PNEUMATIC SOLENOIDS OF THE LOX-30 SYSTEM

The Weibull distribution is widely used in engineering situations because of its versatility. It was originally proposed for the interpretation of fatigue data, but now its use has extended to many other engineering problems. The usefulness of the Weibull distribution stems from the use of straightline plots to represent experimental data. Special Weibull plotting paper is required but the graphical interpretation is reasonable straight forward. Although the Weibull distribution can be applied to most any engineering problems, its main application is in the field of failure life situations. In general, the Weibull distribution best describes the parameters of parts or its components, while the exponential distribution is most applied to assemblies and systems.

The Weibull cumulative distribution function is:

$$F(x) = 1 - \exp\left[- \left(\frac{x-x_o}{\theta-x_o} \right)^b \right]$$

Where:

x_o = expected minimum value of x (location parameter)

b = Weibull slope (shape parameter)

θ = characteristic value (scale parameter)

In working with many life phenomena it is reasonable to assume, as in the case of the solenoid switches of the LOX-30 system, that the lower bound of life x_o, is equal to zero. This reduces the Weibull cumulative distribution function to the two-parameter equation:

$$F(x) = 1 - \exp\left[- \frac{x}{\theta}^{\,b} \right]$$

When attempting to calculate the Weibull slope of life data, very cumbersome calculations are needed. Therefore, there is need for a method of expediting the conversion. This is done with a special coordinate paper known as Weibull Probability Paper.

The following are the malfunction times in hours that the solenoid switches did not operate in the automatic mode. (Manual switch required, operation of plant not affected).

224, 442, 482, 558, 764, 855, 893, 902, 1020, 1111, 1212, 1286, 1491, 1696, 1816, 2124, 2371 and 2437 hours.

With use of Weibull Probability Paper the Weibull slope, characteristic life, mean life and the B_{10} life of these switches are calculated.

Life to Incident	Median Ranks %
224	.04
442	.09
482	.15
558	.20
769	.26
855	.31
893	.36
902	.42
1020	.47
1111	.53
1212	.58
1286	.64
1491	.69
1696	.74
1816	.80
2124	.85
2371	.91
2437	.96

Plotting the data on Weibull Probability Paper, the estimate of the Weibull slope is 1.8. It is known that the log-normal distribution has a Weibull slope of 2.0; therefore, it is reasonable to assume that the solenoid switches failure rate follows the log-normal distribution. For a higher accuracy, this line could be fitted by the least-squares method.

Characteristic Life

By definition, characteristic life θ is the life corresponding to 63.2% failure.
Therefore, θ = 1380 hours

Mean Life

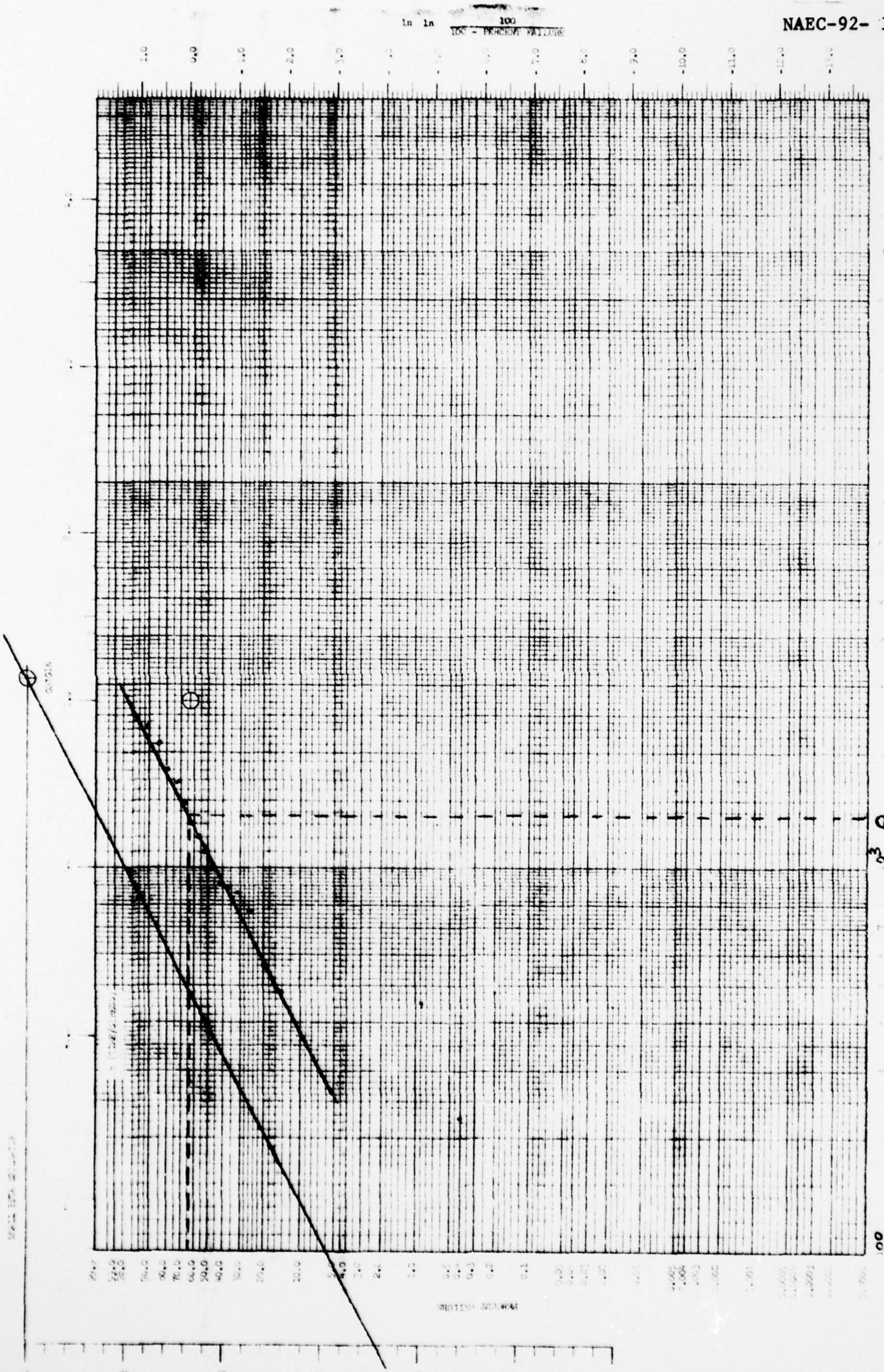
The percent failed is mean = 55.5% for b=1.8. From the Weibull Plot corresponding to 55.5% is

Mean Life = 1200 hours

B_{10} Life

The life corresponding to 10% failure is B_{10} = 380 hours.

It can be said that 10% of the population is expected to have life less than or equal to B_{10} life 380 hours.


ln ln $\frac{100}{100 - \text{PERCENT FAILURE}}$
PERCENT FAILURE
θ
β
100

4E

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